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Liquid swine manure as a phosphorus source for corn-soybean rotation

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Liquid swine manure as a phosphorus source for corn-soybean rotation

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has met the dissertation requirements of Iowa State University

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For the Major Program

To:

Pablo

Diego and Marcia

Mario and Rosana

My parents, Heriberto and Esther

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CHAPTER 1. GENERAL INTRODUCTION

Swine (*Sus scrofa domesticus*) production has intensified in some areas of the Corn Belt and other regions of the USA since the late 1970's and, consequently, the amount of manure produced has also concentrated. This process was accompanied by increased size of feeding operations. Liquid manure is the most common form of storing and handling swine manure, and its application to soils before planting crops is one of the most economical uses. Manure often is applied to soils to supply crop N needs. However, manure is also a valuable source of P and other essential crop nutrients. In Iowa, for example, more than 15,000,000 hogs are produced annually and about 40,000 Mg of P is excreted annually. This large amount of P requires the development of sustainable manure management for agronomic and environmental reasons.

Manure P management is more complicated than fertilizer management for various reasons. Many farmers prioritize disposing of the manure over utilizing it as a source of nutrients for crops. This attitude is explained mainly by difficulties at handling manure, because of the large volume needed to supply a specific amount of nutrients and its physical form. Many other farmers consider mainly manure N content and not P content when deciding to apply manure according to crop needs. Moreover, some apply additional P fertilizer even after applying large amounts of manure. Manure applied to supply N needs of crops such as corn may cause a significant buildup of P in the soil because the P to N ratio in manure usually is higher than the ratio of crop needs.

However, other factors also explain farmers' practices. Two important factors are large variability of nutrient concentrations in manure as well as uncertainty about the proportion of nutrients that will become available for crops. The nutrient concentration in manure is highly variable, and analyses of many samples previous to application are needed for appropriate utilization of manure nutrients. For example, a recent survey conducted in Iowa showed that the concentration of P in liquid sources ranged from 0.1 to 6.6 g of P L^{-1}. Genetic, diet, and age of animals and management of manure during storage cause this variability. Producers and researchers alike are uncertain about manure P availability for crops. For example, guidelines for P availability in manure range from 40 to 100% of the total P concentration for the first year after application across the North Central region. There is a large variation of organic P concentration in animal manures, and often it is assumed that this P fraction is not immediately available for plants.

Soil P test has been the main tool used to assess plant P availability in soils, and acids or bases are used to dissolve and desorb P from soils. However, there are several potential problems with soil P testing for manured fields. There is uncertainty about the value of soil testing, commonly used soil P tests, and existing calibrations for manured fields. Also, with increasing eutrification of surface water resources because of excess P movement off agricultural fields, researchers have proposed new tests that theoretically better evaluate soil P that might be transported with surface runoff or subsurface drainage and P that can stimulate algal growth in streams and lakes. However, there is no conclusive indication that these tests assess soil P differently from routine soil P tests, correlate better with P loss from fields, or assess soil P differently in manured or fertilizer fields.

Recent georeferencing and application technological developments may help management of liquid manure for crop production. Although variable-rate technology has been available to producers for applying granulated or liquid fertilizer for almost a decade, only recently has this technology been adapted to liquid manure. Major assumptions when using this technology on the basis of soil-test P and crop needs are that appropriate rates can applied over a field and that variable application reduces soil-test P variability. Although both research and field observations suggest variable-rate application equipment can apply manure at different rates, there is little or no evidence of its impact on soil-test P levels and variability. Moreover, several statistical procedures can be applied to study soil-test P variability after using variable and fixed P application methods, but these methods may not give similar results or conclusions.

Therefore, for several reasons there is need for more studies on utilization of liquid swine manure P and to provide information for improving management guidelines that would alleviate producers' uncertainty about its use. This improvement should result in more efficient use of this resource and in reduced risk of excess P loss from fields and impaired quality of surface water resources. Therefore, two different studies were conducted using liquid swine manure on both corn and soybean crops to achieve these general goals. One study was conducted on farmers' fields using conventional research plot methodology with objectives to evaluate (a) manure P effects on early corn and soybean plant growth, early P plant uptake, grain yield, and P removal with grain harvest, (b) crop response to fertilizer P applied in addition to manure P applied once for two crops; and (c) evaluate liquid swine manure P application on soil P measured with several routine soil-P tests and two environmental tests. The second study was also conducted on farmers' fields but using a strip-trial methodology using precision agriculture technologies and its objective was to use alternative statistical methods to study soil-test P spatial variability after applying liquid swine manure using variable- and fixed-rate application methods.

DISSERTATION ORGANIZATION

This dissertation is presented as three papers intended for publication in scientific journals of the American Society of Agronomy. The title of the first paper is "Liquid Swine Manure Phosphorus Utilization for Corn and Soybean Production". The second paper is entitled "Effect of Liquid Swine Manure Application for Corn-soybean Rotations on Soil Phosphorus Using Routine and Environmental Soil Tests". The title of the third paper is "Soil-Phosphorus Test Response to Fixed- and Variable-Rate Liquid Swine Manure Application for Soybean-corn rotations". Each paper contains an abstract, introduction, materials and methods, results and discussion, conclusions, reference list, tables, and figures. The papers are preceded by a general introduction and succeeded by a general summary.

CHAPTER 2. LIQUID SWINE MANURE PHOSPHORUS UTILIZATION FOR CORN AND SOYBEAN PRODUCTION

A paper to be submitted to Soil Science Society of America Journal

Mónica M. Barbazán and Antonio P. Mallarino

ABSTRACT

There is uncertainty about manure P availability for crops and need for P fertilization in manured fields. This study evaluated effects of liquid swine manure P application on early growth, grain yield, and P uptake of corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] and crop response to P fertilization in addition to manure application. Sixteen trials were conducted in Iowa from 200o to 2003, and residual effects of manure on a second crop were evaluated at 14 of these trials. Treatments were liquid swine manure (one to twice N or P crop need) and four P fertilizer rates (0 to 30 kg P ha^{-1}) arranged in a randomized, complete-block split-plot design with three to four replications. Soil-test P (STP) was 11 to 89 mg P kg^{-1} across sites (Bray-1 test, 0 to 15-cm depth). High STP variation in several sites agrees with observations from manured fields in previous studies. Measurements were plant growth and P uptake at the V5-V6 growth stage, grain yield, and P removal with grain harvest. Grain yield response to manure application was observed at five sites and to P fertilization at three sites. All responsive sites, except for one had STP < 20 mg P kg^{-1}. Phosphorus fertilizer did not increase grain yield at any site when applied in addition to the high rate of manure. Study of plant responses for similar rates of manure or fertilizer P indicated slightly higher and more frequent early plant growth for manure application compared to fertilization application. The results demonstrated that liquid swine manure is a valuable resource of P for crop production and provided no evidence for lower season-long availability of P in manure compared with P in fertilizer for crop growth or grain yield.

INTRODUCTION

Swine (*Sus scrofa domesticus*) production has been concentrating in areas of the USA Midwest and other regions in recent years and consequently the amount of manure produced and applied to fields in these areas has increased. The increase of the amount of manure has generated a need for improved application equipment, storage facilities, and manure management practices. Liquid manure frequently is applied to soils either as a source of nutrients or as a waste product. In Iowa, about 40,500 Mg of P are excreted annually with swine manure. This large amount of P needs to be managed efficiently to optimize farm profitability and water quality protection. Manure nutrients are a valuable resource and both excess P application and poor P application methods increase the risk of P delivery from fields and eutrophication of water resources.

Management of animal manure in agriculture requires more attention than inorganic fertilizer due to several reasons. Manure application rates for corn and other crops usually are based on manure N content and crop N requirement or removal. Manure application to provide crop N requirements may increase soil levels of P and other nutrients, because the P:N ratios in manure often are significantly higher than P:N ratios needed when supplying these nutrients for crops (Sharpley et al., 1984; Heathwaite et al., 2000). Application of N-based manure rates can result in two to three times more P applied compared with a P-based manure application, and additional P accumulates in soils. Furthermore, uncertainty associated with N and P concentration in animal manure and the plant availability of these nutrients usually leads to over-application of manure and application of additional fertilizer to ensure an adequate nutrient supply for crops.

Phosphorus concentration in manure is highly variable, and this generates a need for analyzing many manure samples previous to application. A recent survey conducted in Iowa (Lorimor and Kohl, 1999) showed that the concentration of P in liquid sources ranged from 0.1 to 6.6 g of P L^{-1}. Animal genetic, diet, and age of animals and management of manure during storage cause this variability. Manure analysis is, therefore, one of the key factors to consider when managing animal manure as a nutrient source. Uncertainty about manure P availability for crops is evident in university manure management recommendations. For example, Iowa guidelines suggest that 60% of total P in animal manure is plant available in the first year of application (Killorn and Lorimor, 1999). However, this value ranges from 40 to 100% in the North Central region [J. Peters, 2004, unpublished, report to the North Central Region Soil Testing Committee (NCR-13)]. There is a large variation of organic P concentration in animal manures, and often it is assumed that this P fraction is not immediately available for plants. For example, Sharpley and Moyer (2000) reported 10% or less is organic P in liquid swine manure. Also, He and Honeycutt (2001) suggested that 49% of P in dry swine manure is organic, although 43% is an easily hydrolysable simple monoester.

There is no consistent information about differences between manure sources in plant availability of the P. Griffin et al. (2003) found that KH_2PO_4 was more efficient at increasing a readily available P pool (P extracted by $CaCl_2$) and a more recalcitrant P pool (Mehlich-3 extractable P) than various manure sources three months after P application. Some studies suggest that manure P may be equally available to P fertilizer or even more available during the first year after application (Laboski and Lamb, 2003; Leytem et al., 2004). Laboski and Lamb (2003) compared liquid swine manure with inorganic P fertilizer and concluded that the availability of manure P was higher than for fertilizer from 1 through 9 months of incubation as evaluated by the Bray-1 test. They explained this result by reduced P sorption by soil constituents due to organic acids resulting from manure decomposition. Siddique and Robinson (2003) also speculated that organic acids released from cattle slurry could block soil P sorption sites resulting in higher availability of P from manure than from inorganic fertilizer.

The effect of P fertilizer application on corn and soybean yield, plant P composition, and soil P has been studied extensively over the years. For example, results of numerous studies from Iowa have been published during the last decade (Mallarino and Blackmer, 1992; Webb et al., 1992; Mallarino, 1996; Bordoli and Mallarino, 1998; Buah et al., 2000; Borges and Mallarino, 2000; Wittry and Mallarino, 2004; Dodd and Mallarino, 2004). However, effects of P from liquid swine manure on early plant growth, early P uptake, grain yield, and P removal have received less attention. Published studies with liquid swine manure from Iowa and other regions of the USA have involved Coastal bermudagrass [*Cynodon dactylon* (L.) Pers.] (Burns et al., 1990) and corn or soybean (Sutton et al.,1982; Atia and Mallarino, 2002; Wittry and Mallarino, 2002). Atia and Mallarino (2002) did not measure grain yield in their Iowa study but showed that early corn and soybean growth, P concentration, and P uptake increased when various rates of liquid swine manure were applied to soils with P near optimum or lower for these crops. Wittry and Mallarino (2002) demonstrated that variable-rate liquid swine manure application based on soil-test P (STP) is feasible and reduces STP within-field variability although its use may not increase grain yield compared with a uniform application method.

Therefore, more research is needed regarding the potential of manure to supply crop P needs and to help producers achieve more efficient nutrient management. The objectives of this study were to evaluate (a) liquid swine manure P effects on early plant growth, plant P uptake, grain yield, and P removal in corn-soybean rotation and (b) crop response to P fertilization in addition to manure application for a first crop and for a second crop without a new manure application.

MATERIALS AND METHODS

Sixteen field trials involving liquid swine manure and P fertilization for corn and soybean were conducted in Iowa from 2000 through 2002. Fourteen of these trials were evaluated for a second year to study residual effects of manure P on a following crop. All trials were established on farmer's fields and soil and crop management practices (except N, P, and K fertilization) where those normally used by each farmer. The fields were managed with corn-soybean rotations, except Site 4 that had alfalfa as previous crop. Corn-soybean rotations were used in the 14 sites that were evaluated for 2 years, except in Sites 7 and 9 where corn was planted after corn. Table 1 contains information about crop hybrids or cultivars, planting date for the first-year crop, soil series, and selected chemical properties of the soils measured before treatment application.

Treatments were application rates of liquid swine manure and P fertilizer that were arranged in a randomized, complete-block split-plot design with three to four replications. The manure treatments were randomized to large plots of each block, and were a control that received no manure, and two to three manure rates that ranged from 17 to 99 kg P ha^{-1} across sites. Table 2 shows information about manure application method and rates. Manure nutrient concentrations are average of at least four samples collected during application. Manure application rates for corn were intended to supply 80 kg N ha^{-1} or 160 kg N ha^{-1} assuming that all manure N was available for the crop. The high N rate used is in the upper range of the fertilizer N rates recommend in Iowa for corn grain production after a soybean crop (Blackmer et al., 1997). The manure rates for soybean as first crop were intended to supply approximately one-half (100 kg N ha^{-1}) or total (200 kg N ha^{-1}) expected average N removal with grain harvest, except at Sites 3, 8, and 15 where they were based on grain P removal. The manure was collected from underground storage pits in farms near each site, and was applied in fall (November) before snow or soils froze or in spring (April or May) three to four wk before planting crops. The manure plots were at least 40 m in length and width varied from 7.5 to 13.5 m depending on the width of the commercial applicator used and the crop planter size. The manure was injected to a depth of 10-15 cm or was broadcast and incorporated into the soil by field cultivation and/or disking within 24 hr of the application. The applicators were calibrated in the field immediately before applying treatments by weighing the tanks before and after preliminary test runs. The P fertilizer treatments were applied to subplots superimposed to each manure main plot.

The length of each subplot was 12 m and the width varied to accommodate four or six crop rows depending on planter size and row spacing (76 or 97 cm). The fertilizer rates were 0, 10, 20, and 30 kg P ha^{-1} (triple superphosphate) broadcast by hand in spring and incorporated by disking. Nitrogen (urea) was applied across all corn plots at 150 kg N ha^{-1} for corn after soybean and 200 kg N ha^{-1} for the two sites with corn after corn. Potassium fertilizer (KCl) was applied at 56 kg K ha^{-1} across all corn and soybean plots. For second-year crops at the 14 sites, manure treatments were not reapplied but P fertilizer treatments and the uniform N and K fertilizer rates were reapplied as appropriate for both crops. Fertilizer P was not reapplied for the second-year of experiments established in 2000.

Initial composite soil samples (12 cores) were collected in spring from a depth of 0 to 15 cm from each large plot and replication before applying the treatments. Composite soil samples also were collected from each subplot after harvesting the first and second crops. Samples were dried at 30 to 40 °C, crushed to pass a 2-mm sieve and analyzed for P with the Bray-1 test, K with the ammonium-acetate test, and pH using a 1:1 soil:water ratio following procedures recommended for the North Central Region (Brown, 1998). Soil organic matter was measured with a combustion method (Wang and Anderson, 1998).

The aboveground parts of 10 plants were sampled at the V5 to V6 growth stage from all plots in all sites. Plants were weighed before and after drying at 65 °C in a forced-air oven to calculate plant dry weight, ground to pass a 2-mm sieve, and digested using a H_2SO_4-H_2O_2 method (Digesdahl Analysis System, Hach Inc., Boulder, CO). Plant P concentration in the digests was determined with the Murphy and Riley (1962) colorimetric method. Phosphorus uptake was calculated from plant P concentrations and plant dry weights. Corn and soybean grain was hand-harvested from 7.5 m of the central two rows (from where plant samples were not collected). Corn grain yield was adjusted to 150 g kg^{-1} moisture and soybean grain yield was adjusted to 130 g kg^{-1} moisture. A sample of grain was dried at 65 °C, ground to flour particle size in a small flour mill, and digested to determine grain

P concentration using the procedure described for the small plants. Grain P removal was calculated from grain P concentrations and yields.

Analysis of variance for a randomized, complete-block split plot design was used to assess the effect of manure and fertilizer treatments and their interactions for all measurements using the GLM procedure of SAS (SAS Institute, 2000) assuming fixed effects. When the analysis of variance indicated that manure application, P fertilization, or their interaction was significant ($P \leq 0.05$) treatment mean differences were tested by orthogonal comparisons. The orthogonal comparisons for manure were control versus the average of the manure rates and low rate versus high rate (or the mean of the low high rates for a site where three manure rates were applied). The orthogonal comparisons for the P fertilizer treatments were control versus the average of the three P rates, 10-kg rate versus the average of the 20- and 30-kg rates, and 20-kg versus the 30-kg rate. The sums of squares of the interaction were partitioned to assess the response to fertilizer for each manure rate and response to manure when no P fertilizer was applied. Regression and correlation analyses were conducted using the REG and CORR procedures of SAS to study relationships between selected measurements.

RESULTS AND DISCUSSION

First-Year Crop Response to Manure and Phosphorus Fertilization

The soils of the sites differed markedly in STP as evaluated by the Bray-1 test (Table 1). According to Iowa STP interpretation categories for corn and soybean (Sawyer et al., 2002), three sites that had corn as first crop were low (Sites 1, 5, and 7), two were optimum (Sites 4 and 9), one was high (Site 3), and three were very high (Sites 2, 6, and 8). Among sites that had soybean as first crop, two sites were low (Sites 13 and 14), one was optimum (Site 15), two were high (Sites 11 and 16), and two were very high (Site 10 and 12). Analysis of soil samples collected from each manure treatment and replication before applying P fertilizer treatments reveled high STP variation at some sites. Standard deviations in Table 1 indicate high STP variation mainly in Sites 3, 6, 10, and 16. High STP variation has been shown before for Iowa manured fields (Mallarino, 1996; Atia and Mallarino, 2002).

Treatment effects on early plant growth and phosphorus uptake.

Plant weights and statistics for average effects of manure and P fertilizer in Table 3 indicate a significant ($P \leq 0.05$) response to manure application at three corn sites (Sites 1, 2, and 8) and three soybean sites (Sites 12, 13, and 14), and a response to P fertilizer only at one corn site (Site 5). There were no significant interactions between manure and P fertilizer at any site for either crop. Plant responses were not obviously related to initial STP. Four responsive soils tested low in STP and three soils tested very high (Table 1). Results from other studies (Ritchie et al., 1995; Gordon et al., 1997) show that temperature and hybrids are important factors explaining early plant growth response to P. Previous Iowa research with P fertilizer (Mallarino et al, 1999; Borges and Mallarino, 2000; Borges and Mallarino, 2003) also showed that corn and soybean early growth response to P was not related to STP. Although manure application usually produced heavier plants compared with no manure application, plant weights for plots receiving the low manure rate did not differ significantly from those receiving the high rate at any corn site. At the two low-testing soybean sites (Sites 13 and 14), however, the high manure rate produced heavier plants than the low rate. Results reported by Atia and Mallarino (2002) for three Iowa soils also showed that an approximately similar low rate of liquid swine manure increased early corn or soybean growth but no further increase was observed when higher manure rates were applied.

Less frequent early plant growth response to P fertilizer than to manure cannot be explained with certainty. For example, manure application did not increase early growth at the low-testing Site

5 but P fertilizer did. Although the manure P rates applied at this site were the lowest of all sites, the high rate applied 35 kg P ha^{-1}, slightly more P than the 30-kg fertilizer rate. However, P fertilization did not increase plant growth in the six corn or soybean sites where manure did. Although the highest fertilizer rates were lower than the highest manure rates in this study, the two highest P fertilizer rates often encompassed the low manure rate. Therefore, insufficient P fertilizer cannot explain the lack of pant response to P fertilizer in most sites, except one. Perhaps the uniform N and K rates applied across all plots were not high enough and plant response to manure can be explained by supply of these nutrients, especially N. However, early growth response to manure could also be explained by other nutrients or unknown growth factors in the manure. It is also possible that high STP within-site variability (Table 1) before treatment application in several sites could explain unexpected results.

Irrespective of the reason, the results indicate that liquid swine manure increased early plant growth more frequently than P fertilizer did. A regression of early plant growth with manure on growth with fertilizer further indicated that manure application resulted in a slightly higher early growth increase than fertilizer. Figure 1 shows the relationship between manure and P fertilizer on early growth of corn and soybean for application rates of each source that were similar or within 4 kg P ha^{-1}. Although the slope of the linear relationship did not differ from 1.0 at $P \leq 0.05$ it was 1.1, which indicates a slightly higher growth trend for manure plots.

The mean P concentration of young plants ranged from 2.5 to 5.1g P kg^{-1} dry matter for corn and from 2.9 to 3.8 g P kg^{-1} for soybean (Table 4). Mallarino (1996) showed that 3.4 g P kg^{-1} was an approximate critical concentration value for early corn growth. In this study, the P concentration for corn plants was higher than the proposed value, except for Site 2 and 8. Plant P concentrations and statistics for average effects of manure and P fertilizer in Table 4 indicate a response to manure application at Site 3 (corn) and a response to P fertilizer at Sites 5 and 8 (both corn sites). However, the manure by P fertilizer interaction was significant at Site 5 indicating that fertilizer increased P concentration only when no manure or the low manure rate were applied suggesting an effect of the high manure rate. Neither manure nor P fertilizer affected the P concentration of young soybean plants at any site. The plant P concentration response to manure application at Site 3 is difficult to explain because STP was higher than at other sites where P concentration was not increased. The high variability in STP at this site or other manure factors may explain the observed response. The plant P concentration response to P fertilizer and not to manure in Sites 5 and 8 cannot be explained with certainty. Although the manure by P fertilizer interaction was not significant at these sites ($P \leq 0.05$), data in Table 4 indicate that manure application without P fertilization tended to increase plant P concentration in both sites.

Plant P uptake data and statistics for average effects of manure and P fertilizer in Table 5 shows a response to manure application at two corn sites (Sites 1 and 8) and two soybean sites (Sites 12 and 14), and a response to P fertilizer only at Site 5 (corn). There was no significant interaction between manure and P fertilizer at any site. Manure application increased early plant growth at Sites 1, 8, 12, and 14 and also at two other sites, but did not increase P concentration at any of these sites. Phosphorus fertilization also increased early growth and plant P concentration at Site 5. Results for early plant P uptake are in agreement with other research (Mallarino et al., 1999; Borges and Mallarino, 2003) in showing that P uptake responses tend to follow early growth responses. Figure 2 shows the relationship between early plant P uptake for manured plots and for fertilizer with approximately similar P application rates for each source. The results indicated no difference between the two sources because the linear coefficient of the linear regression did not differ from 1.0 ($P \leq 0.05$) for corn or soybean.

A correlation study across all sites and treatments showed that early P uptake by corn plants was better related to early growth than P plant concentration ($r = 0.95$ for early growth and $r = 0.45$

for P concentration). For soybean, a high and significant correlation was observed between P uptake and early growth ($r = 0.93$), but early growth and P concentration were not correlated ($r = -0.22$, $P = 0.73$). A limited luxury capacity for P uptake of young corn and soybean plants was observed in previous research (Mallarino, 1996; Mallarino et al., 1999; Borges and Mallarino, 2000; Atia and Mallarino, 2002).

Treatment effects on grain yield.

Mean grain yield across sites ranged from 9.4 to 15.5 Mg ha^{-1} for corn and 2.5 to 4.0 Mg ha^{-1} for soybean. Crop yields and statistics for average effects of manure and P fertilizer in Table 6 indicate that manure application increased ($P \leq 0.05$) grain yield at Sites 3 and 7 (both corn sites) and P fertilizer increased grain yield only at Site 5 (with corn). However, significant interactions between manure and P fertilizer in Sites 5, Sites 9, and 11 indicates a yield response at these sites also. At Sites 5 and 9 (both with corn), each source increased yield only when the other source was not applied, which was an expected result. At Site 11 (soybean) the reason for the interaction is not easily visualized, although it indicates a response to manure when no P fertilizer was applied and highly variable response to P fertilizer that was inconsistent across rates and manure treatments. Corn or soybean response to manure or P fertilizer at Sites 5, 7, 9, and 11 is reasonable because the soils tested about 20 mg kg^{-1} STP or less and a response to P should be expected (Mallarino and Blackmer, 1992; Webb et al., 1992; Mallarino, 1997; Sawyer et al., 2002). At Site 3, the response to manure (there was no response to P fertilizer) is difficult to explain because STP was high. This result could be explained by a high STP variability at this site (Table 1). However, perhaps the uniform N rate applied to all corn plots before planting was insufficient to offset a manure-N effect on yield or manure factors other than N or P could explain the response to manure in this high-testing soil.

A lack of grain yield response to P from manure or fertilizer at most sites with STP > 20 mg kg^{-1} is in agreement with current Iowa STP interpretations (Sawyer et al., 2002) and responses to P fertilizer reported by Mallarino and Blackmer (1992), Webb at al. (1992), and Mallarino (1997). These sources indicate a very low probability of a yield response in soils testing > 20 mg kg^{-1} STP (high or very high), a low probability of a small response in soil testing 16 to 20 mg kg^{-1} (optimum), and a higher probability of a large response in low-testing soils. In this study, STP was low in five sites (Sites 1, 5, 7, 13, and 14) and optimum or borderline between optimum and high in three sites (Sites 4, 9, and 11). However, there was a crop response to manure or P fertilizer at only four of these sites (Sites 5, 7, 9, and 11) and in one high-testing site (Site 3, only to manure). An important result was that although at some responsive sites there was a response to manure and not to P fertilizer, at no site was there a response to P fertilizer when the high manure rate was applied (which applied the full N requirements for corn or expected N removal by soybean).

The two no responsive low-testing sites were in soybean and one in corn. Results reported by Webb et al. (1992) showed that soybean yield was increased by annual P applications in most low-testing site-years and in 10 of 14 site-years where STP was optimum. More recent research (Dodd and Mallarino, 2004) indicated a slightly lower critical STP concentration for soybean than for corn. Eghball et al. (2003) suggested that soybean roots would remove P from deeper layers in the soil profile than corn. Responses of both early plant growth and grain yield to manure or P fertilizer application were observed only at one corn site (Site 5). The early growth response due to manure of P fertilizer application at other sites did not translate into a grain yield response. These results are consistent with previous research (Rehm, 1986; Mallarino et al., 1999; Borges and Mallarino, 2000) in suggesting that plant growth during the late growing season can offset early differences in plant growth.

Treatment effects on grain phosphorus concentration and removal.

Mean grain P concentration ranged from 2.2 to 3.1 g P kg^{-1} for corn and from 5.2 to 6.3 g P kg^{-1} for soybean. The means across all sites (2.4 and 5.8 g P kg^{-1} for corn and soybean, respectively) closely agree with average concentrations assumed in Iowa (2.9 and 5.8 g P kg^{-1} for corn and soybean, respectively) for STP maintenance (Sawyer et al., 2002). Mean P removal across sites (28 and 18.6 kg P ha^{-1} for corn and soybean, respectively) also agree closely with Iowa recommendations, which suggest that on average 27 kg P ha^{-1} are removed by a corn yield of 9.4 Mg ha^{-1} and 19.5 kg P ha^{-1} are removed by a soybean crop yield of 3.4 Mg ha^{-1}.

Grain P concentrations and statistics for average effects of manure and P fertilizer in Table 7 indicate a response ($P \leq 0.05$) to manure application at three soybean sites (Sites 11, 12, and 13) and no response to P fertilizer application at any site. However, a significant interaction between manure and fertilizer at Site 2 indicated that each P source increased grain P concentration only when the other source was not applied. At the three soybean sites, manure application increased grain P concentration but P fertilization did not. The highest manure rate increased the P grain concentration over the low rate. One of the responsive sites (Site 13) was low in STP while all others were high or very high. These results would indicate luxury uptake of P in grain, which has been showed before for fertilized corn in Iowa (Mallarino, 1996).

Phosphorus removal in grain and statistics for average effects of manure and P fertilizer in Table 8 indicate a response ($P \leq 0.05$) to manure at two corn sites (Sites 3 and 7) and statistically borderline ($P \leq 0.06$) at two soybean sites (Sites 11 and 13), and a response to P fertilization at one corn site (Site 4) and two soybean sites (Sites 15 and 16). However, an interaction between manure and P fertilizer was observed at Sites 2, 11 and 15. At Site 2, grain P removal was increased only when each source was applied without applying the other. At Site 11, application of both P sources increased P removal more than either source alone and P fertilizer alone slightly decreased P removal, which is difficult to explain. At Site 15, there was higher P removal when both manure and fertilizer were applied. Responses of both grain yield and P removal with grain harvest were observed at Sites 3, 7, and 11. Responses to both grain P concentration and P removal in grain were observed only at Sites 2, 11, and 13. Therefore, P removal responses at Sites 4, 15, and 16 might be explained by small grain yield or P concentration responses that did not reach statistical significance.

Correlation studies across all sites and treatments showed high and significant correlation between grain P removal and yield ($r = 0.64$ for corn and $r = 0.97$ for soybean), and between P removal and grain P concentration ($r = 0.41$ for corn and $r = 0.64$ for soybean). These results agree with results reported by Mallarino (1996) and Eghball et al. (2003, who found that the amount of P removed by corn or soybean grain depended mainly on the grain yield and sometimes also on grain P concentration.

Summary of first-year crop responses.

Early plant growth responded to manure application at six sites and to P fertilization at one site. Early plant P uptake responded to manure application at four sites and to P fertilization at one site. These early plant responses were observed in soils with STP ranging from low to very high. Therefore, these results indicate that manure applied alone increased early growth and P uptake more frequently than P fertilizer alone did. Regression analyses across all sites with manure and fertilizer that received approximately similar P rates confirmed higher early plant growth with manure application than with fertilizer application, but the difference was small and did not reach statistical significance at ($P \leq 0.05$). Therefore, results of this study provided no evidence for the common concern that swine manure P may not be as effective as P fertilizer for supplying P for early crop growth. Our results are consistent with the very high concentration of orthophosphate P typically found in liquid swine manure (Sharpley and Moyer, 2002).

Grain yield responded to manure application at five sites and to P fertilization at three sites. All responsive sites, except for one responsive to manure, tested optimum or lower in STP. Phosphorus fertilizer did not increase grain yield further when the high rate of manure was applied at any site. Manure application increased P removal in grain at seven sites and P fertilization increased P removal at six sites. Application of both sources together increased P removal further than either source alone at one site. These results provide no evidence for the common concern about manure P being less effective than fertilizer P for increasing grain yield. The results were clear at demonstrating that P fertilization did not increase yield further after applying manure rates that supply the N needs of corn.

Response of Second-Year Crops After Manure Application

Residual effects of manure treatments applied prior to a first crop on a second corn or soybean crop were evaluated at 14 sites. Table 9 shows information about planting dates, hybrids, soybean varieties, and STP measured on soil samples collected from plots receiving no manure or fertilizer after harvesting the previous crop. The site code uses the suffix "b" to denote the correspondence of the second-year site with the site code of first-year. Six sites had corn after soybean (Sites 11b through 16b), two had corn after corn (Sites 7b and 9b), and six had soybean after corn (Sites 1b through 6b, and 8b). Fertilizer P treatments were reapplied at most sites, except for Sites 1b, 11b, and 12b, to assure that P was not limiting for at least some treatments in order to evaluate residual effects of manure P. Therefore, a discussion of manure residual effects on crop measurements will be emphasized in this section while potential differences between crop response to the various P fertilizer rates used will not.

Treatments effects on early plant growth and phosphorus uptake.

Manure applied for a previous crop influenced ($P \leq 0.05$) plant weight of second-year crops at three corn sites (Sites 7b, 14b, and 15b) and one soybean site (Site 1b) (Table 10). Phosphorus fertilizer application increased plant growth in Sites 1b and 9b. Although main effects were not significant at Site 1b, a significant manure by P fertilizer interaction indicated that the combination of manure application with the highest P fertilizer rate increase plant growth over the control. This result is reasonable because P fertilizer treatments were not reapplied at this site. The lack of treatment interactions at other sites indicates that the residual effect of manure was similar across plots that received or did not receive P fertilization. Plant weights were lower for plots that received manure than for the control plots at Site 7b, but were higher for the manured plots at the other responsive sites. Soil-test P of control plots at Site 7b was low before planting the second crop, so we expected some early growth response to manure (Table 9). This site was one of two sites with corn as previous crop, and manure application increased grain yield of the previous crop (Table 6). Therefore, a negative residual response to manure at this site could be associated to increased amount of corn residue (which we did not measure). Dalal (1979) and Salas et al. (2003) showed higher P and N immobilization at manured plots because of larger amount of corn residues compared to plots without manure. Also, decreased soil temperature due to increased residue cover cold have inhibited early plant growth in the manured plots because Kaspar et al. (1990) found that residue removal from the crop row at planting time increased plant height compared with no residue removal. Higher plant weights for manured plots at Sites 14b and 15b is in agreement with increased STP for the manured plots compared with low-testing control plots (Table 9).

The P concentration of young plants for second-year crops ranged from 2.8 to 5.1 g P kg^{-1} of dry matter for corn and 2.8 to 3.8 g P kg^{-1} for soybean (Table 11). The range and mean values were similar to those for corn or soybean first-year crops after manure application. Manure application before the previous crop influenced P concentration of young plants of second-year crops at two soybean sites (Sites 3b and 4b) and three corn sites (Sites 12b, 13b, and 15b). Main effects were not significant at Sites 3b 13b, and 15b, but a significant interaction between manure and P fertilizer indicated a significant residual effect of manure applied for a previous crop on plant weight when P fertilizer was not reapplied. At Site 4b, an increased plant P concentration due to manure applied for the previous crop suggests luxury accumulation of P in the plants because STP was very high and neither manure nor P fertilizer increased early plant growth at this site. At Site 12b, plant weights were higher for both manure rates compared with the control, although the increase was higher for the low rate probably due to higher plant growth for the high manure rate that did not reach statistical significance. It is interesting to note that in Site 7b, where plant weights were lower with manure than for the control, plant P concentrations did not differ across manure treatments (although tended to be lower with manure) but increased with increasing P fertilizer rates.

Plant P uptake was influenced by manure application before a previous crop at four corn sites (Sites 7b, 8b, 13b, and 15b) and at one soybean site (Site 1b) (Table 12). The main effect of manure was not significant ($P \leq 0.05$) at Sites 1b and 8b but significant interactions between manure and P fertilizer indicated that manure influenced plant P uptake where P fertilizer was not applied. Plant P uptake was lower for manure application than for the control at Site 7b, which agrees with lower early growth with manure. Plant P uptake with manure was higher than for the control at the other four sites, which agrees with early plant growth responses at Sites 1b and 15b and a plant P concentration response at Site 13b. The P uptake response at Site 8b probably is explained by not significant responsive trends for both early plant growth and P concentration.

Correlation studies across sites and treatments showed that plant P uptake for corn was positively correlated with early growth and plant P concentration ($r = 0.92$ and $r = 0.72$, respectively). However, plant P uptake for soybean was correlated with early growth but poorly correlated with plant P concentration ($r = 0.85$ and $r = 0.22$, respectively). These results are in agreement with results for first-year crops.

Treatments effects on grain yield.

Manure applied before the previous crop and reapplied P fertilizer treatments seldom influenced ($P \leq 0.05$) grain yield of corn or soybean second-year crops (Table 13). A small grain yield response was observed only at Site 3b (soybean) and only to reapplied P fertilizer treatments. Furthermore, the average yield response to P across all manure rates at this site, although small, is difficult to explain because STP of control was very high (Table 9). A yield response was expected at least for sites in which the control plots tested low in STP, which were Sites 1b, 13b, and 14b. A small yield response could also have been expected in sites with optimum STP (Sites 7b, 8b, 9b, and 15b). We suspect that the isolated small crop response observed at the high-testing Site 3b was a random result.

Treatments effects on grain phosphorus concentration and removal

Mean grain P concentrations ranged from 1.8 to 2.8 mg P kg^{-1} for corn 4.6 to 6.9 g P kg^{-1} for soybean. These ranges were similar to those found for first-year corn or soybean crops after manure application. The mean grain P removal for corn ranged from 15.1 to 36.4 kg P ha^{-1}, with an average value of 26 kg P ha^{-1}. The P removal range for soybean was 9.7 to 27.6 kg P ha^{-1}, with an average value of 17 kg P ha^{-1}. Probably because grain yield was slightly lower for the second-crop sites than for the first-crop sites, mean grain P removal across all second-year sites also were lower (9% lower for corn and 7% lower for soybean). The two-year average P removal for the rotation approximately agree with ISU recommendations, which suggest 46 kg P ha^{-1} of P removal for the two-year rotation assuming 9.4 Mg ha^{-1} yield of corn and 3.4 Mg ha^{-1} yield of soybean (Sawyer et al., 2002).

Manure application before the previous crop influenced ($P \leq 0.05$) the grain P concentration only at one soybean site (Site 1b), where there was also a response to manure for all P fertilization rates. At Site 13b, P fertilizer increased grain P concentration across all manure application rates.

As expected from the very few grain yield and P concentration responses, manure application before a previous crop or fertilizer application seldom influenced ($P \leq 0.05$) P removal with grain harvest (Table 15). Responses were observed only to P fertilizer reapplied at Sites 6b (soybean) and 13b (corn). Clear responsive trends were also observed at these sites for manure when no fertilizer was applied but differences did not reach statistical significance ($P \leq 0.05$). Soil-test P of the control treatments was high at Site 6b and low at Site 13b. It is remarkable that no response was observed at other sites. Because manure or P fertilizer seldom increase yield of the second-year crops, we expected some increase in grain P concentration because previous research (Mallarino, 1996) showed luxury P accumulation in grain and we observed some of that for first year crops.

Summary of treatment effects on second-year crops after applying manure.

Manure applied before the first-year crop or reapplied P fertilizer treatments seldom influenced crop growth, yield, or P uptake of second-year crops. Higher early plant weights were observed in manured of fertilizer of three sites compared with the control. In one other site where corn was planted after corn, plant weight was lower for manure than for unmanured or fertilizer probably because of inhibitory effects of increased residue from a responsive first-year corn crop. Manure applied before the previous crop or reapplied P fertilizer treatments increased early plant P concentration at five sites. Early plant P uptake was higher for manured plots of four sites compared with the control, but was lower with manure of a site where early plant weight was lower. The higher plant P uptake in manured plots at other sites sometimes coincided with higher plant growth and other times with higher plant P concentration. Response of grain yield, P concentration, and P removal to manure applied before the previous crop or reapplied P fertilizer treatments were even less frequent than for early plant growth and P uptake (to reapplied P fertilizer treatments in one site). A lack of general response to P for second-year crops cannot be explained because several sites were low in STP and P fertilizer treatments were reapplied at most sites.

CONCLUSIONS

Liquid swine manure and P fertilizer application increased early corn and soybean growth, early P uptake, grain yield, and P removal in grain at few sites because STP was higher than needed to maximize growth and yield and because of very high STP variation in some sites. Early plant growth and P uptake responses were not related to initial STP, which is a result in agreement with previous research with P fertilization in Iowa. Study of plant responses to manure or fertilizer at approximately similar P rates indicated slightly higher and more frequent early plant growth with manure application compared with fertilizer application, but the difference was small. Therefore, results of this study provided no evidence for a lower effectiveness of liquid swine manure P compared with P fertilizer for supplying P for early crop growth.

Grain yield response to manure application was observed at five sites and to P fertilization at three sites. All responsive sites, except for one site responsive to manure, tested optimum or lower in STP. This result is reasonable because crop response to P is expected in those interpretation classes. Phosphorus fertilizer did not increase grain yield further when the high rate of manure was applied at any site. Therefore, either random effects or factors other than P in manure could explain the more frequent grain yield response to manure than to P fertilizer. The second-year crop after manure application seldom responded to residual manure P or to reapplied P fertilizer treatments, which was a result we could not explain. The observed grain yield responses for first-year or second-year crops provide no evidence for lower availability of manure P compared with fertilizer P for grain yield. An important result was that P fertilizer application in addition to manure rates that approximately supply N needs of corn did not increase grain yield further at any site.

Overall, the results of this study showed that liquid swine manure is a valuable resource of P for crop production and provided no evidence for a lower availability of P in manure compared with P in fertilizer for early crop growth or grain yield. The high STP variation observed in several sites agrees with observations from other manured fields and is explained by difficulty in applying manure uniformly.

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Table 1. Field locations and predominant soils series for first-year corn and soybean crops.

Site	Year	Crop	Hybrid or Variety	Planting date	Predominant soil Series	Predominant soil Classification†	Soil Chemical pH	Soil Chemical STP‡	Soil Chemical STK§	Soil Chemical OM¶
								... mg kg^{-1}...		g kg^{-1}
1	2000	Corn	Garst 8559 RR Bt	22 May	Webster Nicollet	T. Endoaquoll A. Hapludoll	6.5	14 ± 2	133	53
2	2001	Corn	Cargill 5021 Bt	8 May	Talcot Wadena	T. Haplaquoll T. Haplaquoll	5.2	34 ± 11	259	40
3	2001	Corn	Stine 9616 Bt	14 May	Webster Nicollet	T.Endoaquoll A. Hapludoll	6.2	25 ± 14	177	30
4	2001	Corn	Syngenta (NK) 45 - T5	15 May	Readlyn	A. Hapludoll	7.3	19 ± 4	112	39
5	2001	Corn	Garst 8690	16 Apr.	Marcus	T. Haplaquoll	6.0	11 ± 8	178	64
6	2001	Corn	Pioner 33P67 Bt	2 May	Kalona Taintor	T. Haplaquoll T.Argiaquoll	7.0	49 ± 52	207	59
7	2002	Corn	Stine 9712 RR Bt	16 Apr.	Edina	T. Argialboll	7.0	11 ± 3	84	35
8	2002	Corn	Stine 9614 Bt	5 May	Webster Nicollet	T. Endoaquoll A. Hapludoll	5.5	36 ± 9	130	37
9	2002	Corn	Wyffels 6985 HOC	26 Apr.	Brownton Otosen	T. Haplaquoll A. Hapludoll	6.0	17 ± 9	174	57
10	2000	Soybean	Stine 25342-4 RR	30 Apr.	Clarion	T. Hapludoll	6.1	89 ± 21	208	49
11	2000	Soybean	Stine 2506-4 RR	1 May	Webster Nicollet	T. Endoaquoll A. Hapludoll	6.6	22 ± 5	171	58
12	2000	Soybean	Dekalb CX-242 RR	22 May	Marcus	T. Haplaquoll	6.3	52 ± 6	191	63
13	2001	Soybean	Garst D-261 RR	16 May	Marcus	T. Haplaquoll	6.7	11 ± 3	164	67
14	2001	Soybean	Pioneer 93B72 RR	16 Jun.	Mehaska Nira	A. Argiudoll T. Hapludoll	6.5	13 ± 3	206	40
15	2002	Soybean	Syngenta (NK) S24-K4 RR	16 May	Kenyon	T. Hapludoll	6.7	19 ± 4	98	38
16	2002	Soybean	Praire Brand PB-2821 RR	10 May	Clarion	T. Hapludoll	6.8	27 ± 13	130	46

† T , Typic; A, Aquic.

‡ STP, soil test P (Bray-1), mean and standard deviation.

§ STK, soil-test K (1 *M* amonium acetate). STP and STK in 0-15cm depth samples taken before treatment application.

¶ OM, organic matter.

Table 2. Manure application method and date, manure analysis, and nutrient application rates at each site.

	Manure application				Manure total nutrient analysis			Manure total nutrient applied					
								N		P		K	
Site	Year	Date	Method†	Crop	N	P	K	Low	High	Low	High	Low	High
					.... g L^{-1}			.... kg ha^{-1}					
1	2000	24 Apr.	Injected	Corn	7.0	2.1	3.6	78	156	23	47	40	80
2	2001	29 Apr.	Injected	Corn	5.9	1.8	3.3	102	203	32	63	57	113
3	2001	26 Apr.	Injected	Corn	5.8	2.0	3.1	129	214	44	74	70	115
4	2001	27 Apr.	Injected	Corn	5.6	1.3	3.7	115	232	27	54	75	152
5	2001	15 May	Incorporated	Corn	7.1	1.6	3.2	80	159	17	34	35	72
6	2000	10 Nov.	Injected	Corn	7.3	2.4	3.6	118	212	36	68	58	104
7	2002	05 Apr.	Injected	Corn	6.1	1.8	3.5	78	178	23	53	45	101
8	2001	12 Nov.	Injected	Corn	3.8	0.9	3.0	123	178	29	42	96	139
9	2001	21 Nov.	Injected	Corn	5.6	1.0	3.2	105	211	19	37	59	119
10	2000	30 Mar.	Injected	Soybean	5.3	1.5	3.0	69	93	20	49	40	75
11	2000	24 Apr.	Injected	Soybean	8.5	2.8	3.9	102	204	28	56	55	110
12	2000	27 Apr.	Incorporated	Soybean	8.0	2.3	3.2	128	255	36	71	50	101
13	2001	15 May	Incorporated	Soybean	7.1	1.5	3.2	112	225	26	51	50	101
14	2001	19 Apr.	Injected	Soybean	6.4	1.7	3.0	128	225	33	61	57	106
15	2001	09 Nov.	Injected	Soybean	7.6	2.3	4.8	162	325	49	99	102	205
16	2001	21 Nov.	Injected	Soybean	5.5	1.2	3.4	120	240	26	52	73	147

† Manure was injected or broadcasted and incorporated within 24 hours.

Table 3. Early plant dry weight of first-year corn and soybean crops as affected by manure and P fertilizer applications.

		Corn									Soybean						
Manure	Fertilizer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	kg P ha^{-1}	g pl^{-1}															
Control	0	4.17	1.19	1.95	4.23	2.67	2.06	2.51	3.33	2.13	2.68	1.43	0.50	2.78	2.50	0.97	1.92
	10	3.92	1.54	2.21	4.28	2.93	2.02	2.41	3.57	2.08	2.61	1.25	0.64	2.41	2.54	1.00	1.53
	20	3.86	1.63	2.29	3.94	2.74	2.02	2.27	3.35	2.32	2.63	1.18	0.51	2.55	2.92	0.95	1.79
	30	3.75	1.37	2.11	4.23	3.37	1.89	2.63	3.54	2.25	3.01	1.23	0.54	2.59	2.82	0.98	1.90
	Mean	3.93	1.43	2.14	4.17	2.93	2.00	2.46	3.45	2.19	2.73	1.27	0.55	2.58	2.70	0.98	1.79
Low	0	5.02	1.72	2.40	4.26	2.53	1.64	3.53	4.67	2.64	2.55	1.13	0.65	2.63	3.44	1.02	2.11
	10	4.91	1.59	2.52	4.51	2.36	2.13	3.59	4.38	2.78	2.59	1.31	0.62	2.48	3.21	0.98	1.82
	20	4.79	1.80	2.31	4.44	3.17	1.70	3.74	4.40	2.68	3.28	1.33	0.63	2.98	3.44	1.09	1.77
	30	5.35	1.74	2.13	4.35	3.22	2.10	4.10	4.69	2.83	2.53	1.03	0.66	2.86	4.15	1.09	2.28
	Mean	5.02	1.71	2.34	4.39	2.82	1.89	3.74	4.54	2.73	2.74	1.20	0.64	2.74	3.56	1.05	2.00
High	0	4.90	1.89	2.45	4.38	2.65	3.21	4.18	4.08	2.56	2.64	1.10	0.73	3.74	3.93	1.05	2.72
	10	5.01	1.89	2.26	4.46	3.11	3.04	3.57	4.52	2.89	3.86	1.26	0.71	3.51	4.78	1.15	1.78
	20	4.40	1.98	2.74	4.66	3.22	2.47	4.14	4.70	2.79	2.86	1.42	0.67	3.39	4.25	1.00	2.23
	30	5.44	2.00	2.80	4.37	3.39	3.55	3.83	4.28	2.87	2.96	1.22	0.84	3.42	3.60	1.05	2.17
	Mean	4.94	1.94	2.56	4.47	3.09	3.07	3.93	4.39	2.78	3.08	1.25	0.74	3.52	4.14	1.06	2.23
		Statistical significance ($P > F$)†															
Manure		0.02	0.03	0.17	0.13	0.87	0.06	0.13	0.02	0.14	0.69	0.87	0.03	0.03	0.01	0.37	0.56
Fertilizer		0.51	0.60	0.80	0.71	0.02	0.29	0.50	0.94	0.90	0.78	0.56	0.17	0.62	0.75	0.92	0.06

† No manure by P fertilizer interaction was observed at any site ($P \leq 0.05$).

Table 4. Plant P concentration of first-year corn and soybean crops as affected by manure and P fertilizer applications.

		Corn									Soybean						
Manure	Fertilizer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	kg P ha^{-1}	g P kg^{-1}															
Control	0	3.75	2.72	4.51	4.33	3.81	3.94	4.23	3.16	4.54	3.31	3.06	3.65	2.82	2.74	3.51	3.21
	10	3.98	2.52	4.07	4.02	3.78	3.83	4.16	3.46	4.28	3.31	2.94	3.72	2.86	2.53	3.75	3.07
	20	3.76	2.63	4.71	4.13	4.13	3.94	4.60	3.29	4.43	3.44	2.85	3.61	2.88	2.54	3.49	3.29
	30	3.90	2.27	4.68	4.49	4.19	3.87	4.72	3.58	4.38	3.69	2.81	3.45	2.96	2.68	3.75	3.12
	Mean	3.85	2.54	4.49	4.24	3.98	3.90	4.43	3.37	4.41	3.44	2.91	3.61	2.88	2.62	3.63	3.17
Low	0	4.15	2.64	4.99	4.34	3.88	4.26	4.20	3.29	4.20	3.75	2.79	3.61	2.81	2.68	3.53	2.88
	10	4.26	2.96	4.87	4.28	3.99	3.87	4.24	3.46	4.57	3.72	3.24	3.61	2.92	2.54	3.42	3.24
	20	3.89	2.76	4.74	4.28	4.05	4.07	4.36	3.48	4.39	3.67	3.03	3.46	3.02	2.64	3.40	2.96
	30	4.11	2.83	4.87	4.39	4.19	4.16	4.17	3.79	4.25	3.73	2.84	3.78	2.98	2.47	3.50	3.02
	Mean	4.10	2.80	4.87	4.32	4.03	4.09	4.24	3.51	4.35	3.72	2.98	3.62	2.93	2.59	3.46	3.02
High	0	4.44	3.29	4.89	4.23	3.94	3.88	4.23	3.66	4.42	3.82	3.17	3.98	2.88	2.71	3.78	2.92
	10	4.45	3.34	5.05	4.27	3.78	4.07	4.56	3.86	4.46	3.82	3.07	3.57	3.03	2.66	3.60	3.19
	20	4.60	2.99	5.12	3.97	3.87	3.82	4.24	4.06	4.65	3.45	3.15	3.83	3.18	2.29	3.45	3.13
	30	4.53	2.63	5.26	4.17	3.98	4.05	4.52	3.88	4.41	4.04	3.32	3.88	2.97	2.68	3.59	3.18
	Mean	4.51	3.06	5.08	4.16	3.89	3.96	4.39	3.86	4.49	3.78	3.18	3.82	3.02	2.58	3.61	3.11
		Statistical significance ($P > F$)															
Manure		0.09	0.32	0.02	0.34	0.29†	0.13	0.41	0.09	0.61	0.43	0.31	0.11	0.36	0.84	0.31	0.24
Fertilizer		0.68	0.11	0.27	0.08	0.01	0.53	0.60	0.01	0.67	0.31	0.95	0.42	0.08	0.11	0.29	0.71

† A manure by P fertilizer interaction was observed at Site 5 ($P \leq 0.05$).

Table 5. Plant P uptake of first-year corn and soybean crops as affected by manure and P fertilizer applications.

		Corn									Soybean						
Manure	Fertilizer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	kg P ha^{-1}	......							mg P pl^{-1}								......
Control	0	15.76	3.23	8.79	18.27	10.17	8.05	10.70	10.58	9.61	9.14	4.36	1.84	7.83	6.85	3.41	6.44
	10	15.59	3.91	8.95	17.21	11.03	7.76	10.02	12.46	8.88	8.96	3.76	2.37	6.87	6.42	3.75	4.70
	20	14.64	4.33	10.77	16.29	11.31	7.86	10.43	11.04	10.25	9.17	3.40	1.87	7.32	7.45	3.30	5.88
	30	14.61	3.16	9.87	19.03	14.15	7.35	12.33	12.67	9.83	11.26	3.50	1.86	7.70	7.52	3.69	5.97
	Mean	15.15	3.66	9.60	17.70	11.67	7.76	10.87	11.69	9.64	9.63	3.76	1.99	7.43	7.06	3.54	5.75
Low	0	20.88	4.61	12.05	18.49	9.88	7.10	14.60	15.58	11.26	9.80	3.14	2.36	7.35	9.22	3.61	6.12
	10	20.90	4.62	12.28	19.29	9.43	8.32	15.19	15.43	12.63	9.80	4.33	2.22	7.27	8.18	3.36	5.94
	20	18.72	4.97	11.01	19.01	12.79	6.89	16.61	15.69	11.81	12.37	4.01	2.19	9.02	9.06	3.71	5.23
	30	22.15	5.09	10.36	19.08	13.38	9.09	17.19	18.02	12.12	9.55	2.95	2.50	8.55	10.28	3.81	6.87
	Mean	20.66	4.82	11.42	18.97	11.37	7.85	15.90	16.18	11.95	10.38	3.60	2.32	8.05	9.18	3.62	6.04
High	0	21.72	6.17	12.17	18.54	10.42	12.63	17.71	15.00	11.32	10.21	3.53	2.90	10.76	10.59	3.98	7.97
	10	22.37	6.34	11.40	18.97	11.76	12.44	16.33	17.60	12.79	15.18	3.99	2.55	10.59	12.68	4.13	5.64
	20	20.51	5.92	14.00	18.50	12.27	9.50	17.50	19.18	13.03	10.02	4.48	2.58	10.89	9.68	3.45	6.99
	30	24.64	5.19	14.83	18.24	13.45	14.40	17.48	16.72	12.73	12.11	4.10	3.27	10.27	9.66	3.81	6.91
	Mean	22.31	5.91	13.10	18.56	11.97	12.24	17.25	17.12	12.47	11.88	4.02	2.82	10.63	10.65	3.84	6.88
		Statistical significance ($P > F$)†															
Manure		0.04	0.08	0.06	0.19	0.95	0.07	0.18	0.04	0.13	0.62	0.77	0.03	0.05	0.01	0.60	0.62
Fertilizer		0.50	0.61	0.71	0.59	0.01	0.27	0.45	0.39	0.87	0.82	0.71	0.09	0.63	0.93	0.45	0.31

† No manure by P fertilizer interaction was observed at any site ($P \leq 0.05$).

Table 6. Grain yield of first-year corn and soybean crops as affected by manure and P fertilizer applications.

		Corn									Soybean						
Manure	Fertilizer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	kg P ha^{-1}	Mg ha^{-1}															
Control	0	11.33	10.83	12.20	9.12	9.48	13.62	8.66	13.61	9.17	3.28	2.71	3.84	2.65	2.48	3.99	3.00
	10	11.07	11.60	12.16	9.46	10.49	12.65	7.42	14.34	11.92	3.29	2.54	3.99	2.56	2.64	4.00	2.57
	20	11.25	10.99	11.12	9.50	11.44	13.08	8.37	13.61	11.00	3.27	2.27	3.81	2.63	2.58	3.98	2.47
	30	11.47	11.15	13.03	9.68	10.62	13.40	7.29	14.59	11.22	3.23	2.35	3.85	2.68	2.80	4.01	2.89
	Mean	11.28	11.14	12.13	9.44	10.50	13.19	7.93	14.03	10.83	3.27	2.47	3.87	2.63	2.63	4.00	2.73
Low	0	10.85	11.60	13.28	9.45	10.13	14.90	10.66	13.80	12.17	3.24	2.94	3.84	2.67	2.76	3.92	3.16
	10	11.15	12.40	13.28	9.69	10.91	14.65	9.31	13.52	10.78	3.14	3.11	3.97	2.43	2.83	3.95	3.47
	20	10.83	12.61	12.42	9.33	11.58	14.50	10.77	14.41	12.11	3.18	3.20	3.75	2.64	2.83	3.94	3.22
	30	10.69	12.59	13.24	10.05	11.07	15.31	10.47	13.27	11.83	3.30	2.76	4.03	2.46	2.77	4.15	3.92
	Mean	10.88	12.30	13.05	9.63	10.92	14.84	10.30	13.75	11.72	3.22	3.00	3.90	2.55	2.80	3.99	3.44
High	0	10.93	12.68	14.82	10.07	10.70	15.39	11.64	13.39	11.87	3.21	3.04	3.93	2.72	2.48	3.92	3.37
	10	10.84	12.43	13.56	9.87	11.75	15.34	11.48	14.09	11.61	3.22	3.32	3.67	2.70	2.71	3.99	2.46
	20	10.80	12.08	14.55	10.02	11.04	16.19	10.88	14.13	12.07	3.11	3.17	3.57	2.55	2.67	4.05	3.26
	30	10.72	11.80	14.13	10.00	11.59	15.07	11.59	14.25	12.19	2.85	3.24	3.81	2.67	2.57	4.14	3.45
	Mean	10.82	12.25	14.26	9.99	11.27	15.50	11.40	13.97	11.93	3.09	3.19	3.74	2.66	2.61	4.02	3.13
		Statistical significance ($P > F$)															
Manure		0.54	0.22	0.01	0.18	0.13†	0.12	0.01	0.85	0.38†	0.11	0.12†	0.31	0.31	0.53	0.73	0.70
Fertilizer		0.98	0.40	0.11	0.35	0.03	0.77	0.33	0.45	0.42	0.82	0.22	0.19	0.68	0.21	0.11	0.06

† A manure by P fertilizer interaction was observed at Sites 5, 9, and 11 ($P \le 0.05$).

Table 7. Grain P concentration of first-year corn or soybean crops as affected by manure and P fertilizer applications.

		Corn									Soybean						
Manure	Fertilizer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	kg P ha^{-1}	g P kg^{-1}															
Control	0	2.62	2.10	2.21	2.85	2.11	2.52	2.81	2.24	2.32	5.74	5.70	5.81	5.03	5.85	6.21	5.28
	10	2.59	2.13	2.24	2.64	2.34	2.69	2.89	2.14	1.98	5.82	5.72	5.81	5.14	5.55	6.00	5.93
	20	2.45	2.32	2.26	2.77	2.01	2.41	2.91	2.08	2.47	5.91	5.47	5.72	5.32	5.80	6.20	5.78
	30	2.61	2.22	2.22	2.84	2.32	2.38	2.87	2.35	2.58	6.04	5.41	5.99	5.25	5.93	6.35	6.12
	Mean	2.57	2.19	2.23	2.78	2.20	2.50	2.87	2.20	2.34	5.88	5.58	5.83	5.19	5.78	6.19	5.78
Low	0	2.54	2.30	2.20	2.66	1.96	2.43	3.03	2.17	2.17	5.94	5.57	5.86	5.40	5.87	6.28	5.29
	10	2.59	2.25	2.36	2.71	2.03	2.25	2.87	2.30	2.21	5.94	5.72	5.92	5.30	5.99	6.27	5.30
	20	2.71	2.09	2.36	2.82	2.30	2.10	3.05	2.24	2.06	5.99	5.68	5.97	5.43	5.58	6.30	5.54
	30	2.68	2.35	2.28	2.90	2.33	2.17	3.17	2.34	2.30	6.05	5.68	6.07	5.48	5.89	6.27	6.05
	Mean	2.63	2.25	2.30	2.77	2.16	2.24	3.03	2.26	2.18	5.98	5.66	5.96	5.40	5.83	6.28	5.55
High	0	2.77	2.29	2.57	2.76	2.21	2.04	2.98	2.10	2.25	6.07	5.90	6.10	5.43	5.75	5.99	5.75
	10	2.70	2.24	2.54	2.69	2.37	2.20	3.00	2.02	2.26	5.86	5.90	6.04	5.59	5.80	6.33	5.88
	20	2.79	2.40	2.11	2.72	2.20	2.19	3.20	2.29	2.24	6.07	5.95	6.23	5.67	5.93	6.27	5.53
	30	2.68	2.17	2.40	2.67	2.51	2.33	3.09	2.11	2.29	5.98	5.99	6.11	5.74	5.89	5.95	5.54
	Mean	2.73	2.28	2.40	2.71	2.32	2.19	3.07	2.13	2.26	6.00	5.94	6.12	5.61	5.84	6.14	5.68
		Statistical significance ($P > F$)															
Manure		0.47	0.09†	0.38	0.37	0.45	0.17	0.14	0.18	0.25	0.61	0.01	0.01	0.01	0.92	0.40	0.58
Fertilizer		0.97	0.57	0.74	0.16	0.36	0.76	0.13	0.60	0.29	0.16	0.62	0.27	0.16	0.55	0.72	0.43

† A manure by P fertilizer interaction was observed at Site 2 ($P \leq 0.05$).

Table 8. Grain P removal by first-year corn and soybean crops as affected by manure and P fertilizer applications.

		Corn									Soybean						
Manure	Fertilizer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	kg P ha^{-1}	kg P ha^{-1}															
Control	0	29.7	22.8	26.9	25.9	19.9	35.7	24.3	30.5	21.3	18.9	15.4	22.4	13.3	14.5	24.8	16.0
	10	28.7	24.7	27.2	24.9	24.7	33.9	21.5	30.7	23.7	19.1	14.5	23.2	13.2	14.7	24.0	15.5
	20	27.5	25.5	25.0	26.3	23.1	61.7	24.4	28.4	27.2	19.3	12.4	21.8	14.0	15.1	24.7	14.0
	30	30.0	24.7	30.0	27.5	24.9	31.9	20.9	34.3	28.6	19.5	12.7	23.1	14.1	16.6	25.5	17.5
	Mean	29.0	24.4	27.3	26.2	23.2	33.3	22.8	31.0	25.2	19.2	13.8	22.6	13.7	15.2	24.7	15.7
Low	0	27.4	26.6	29.1	25.1	19.7	36.1	32.4	29.9	26.3	19.3	16.4	22.4	14.5	16.2	24.6	16.6
	10	28.9	27.9	31.4	26.2	22.1	33.0	26.8	31.1	24.0	18.6	17.8	23.5	12.9	16.9	24.8	18.4
	20	29.4	26.3	29.2	26.2	26.9	30.5	32.8	32.4	24.9	19.1	18.2	22.4	14.3	15.8	24.8	17.9
	30	28.6	29.6	30.1	29.1	25.9	33.2	33.3	31.0	27.4	19.9	15.7	24.5	13.5	16.3	26.0	23.9
	Mean	28.6	27.6	30.0	26.7	23.6	33.2	31.2	31.1	25.7	19.2	17.0	23.2	13.8	16.3	25.1	19.2
High	0	30.2	29.0	38.0	27.8	23.5	31.4	34.6	28.1	26.7	19.5	17.9	24.0	14.8	14.4	23.4	19.7
	10	29.3	27.9	34.4	26.6	27.8	33.8	34.5	28.4	26.2	18.9	19.6	22.2	15.1	15.8	25.2	14.5
	20	30.0	29.0	30.7	27.3	24.3	35.5	34.9	32.5	27.2	18.8	18.8	21.5	14.5	15.8	25.4	18.1
	30	28.8	25.7	33.8	26.7	29.1	35.0	35.8	30.0	27.8	17.1	19.4	22.9	15.3	15.1	24.7	19.1
	Mean	29.6	27.9	34.2	27.1	26.2	33.9	35.0	29.8	27.0	18.6	18.9	22.6	14.9	15.3	24.7	17.9
		Statistical significance ($P > F$)															
Manure		0.16	0.12†	0.01	0.47	0.09	0.97	0.01	0.66	0.48	0.29	0.06†	0.60	0.06	0.69	0.80†	0.80
Fertilizer		0.99	0.77	0.23	0.04	0.09	0.84	0.16	0.38	0.32	0.97	0.11	0.15	0.69	0.42	0.03	0.04

† A manure by P fertilizer interaction was observed at Sites 2, 11, and 15 ($P \leq 0.05$).

Table 9. Hybrid or variety, plant date, and phosphorus available in control plots for second-year corn and soybean (crop after manure applied).

Site	Year	Crop	Hybrid or Variety	Planting date	Manure Rate and Soil-test P † Control	Low manure	High manure
					.... mg kg^{-1}		....
1b	2001	Soybean	Patriot 24R09 RR	7 Jun.	15	17	19
2b	2002	Soybean	Asgrow AG 2601	22 May	39	37	48
3b	2002	Soybean	Stine 2463-4 RR	4 May	32	30	32
4b	2002	Soybean	Syngenta (NK) S24-	16 May	31	33	38
6b	2002	Soybean	Pioneer 93 B 72	22 May	46	43	30
7b	2003	Corn	Pioneer 33P67/Dekalb	12 Apr.	15	14	17
8b	2003	Soybean	Stine 2802-4 RR/SSN	22 May	18	24	25
9b	2003	Corn	Wyffels W5534 G	21May	17	34	27
11b	2001	Corn	Pioneer 34G82 Bt	17 May	31	21	33
12b	2001	Corn	Dekalb	15 May	54	57	77
13b	2002	Corn	Garst 8640 IT	24 Apr.	12	20	21
14b	2002	Corn	Pioneer 33 P67Bt	17 Apr.	12	14	17
15b	2003	Corn	Pioneer 36 B 09 Bt	13 May	17	18	28
16b	2003	Corn	Pioneer 33 P 67 Bt	28 Apr.	29	39	24

† Bray-1 P in soil samples at 0-15 cm depth collected after harvesting the first-year crop.

Table 10. Early growth of second-year corn and soybean and a second application of P fertilizer.

Manure rate	Fertilizer rate	Sites†													
		1b‡	2b	3b	4b	6b	7b	8b	9b	11b‡	12b‡	13b	14b	15b	16b
	kg P ha^{-1}	....						g pl^{-1}	....						
Control	0	2.34	2.71	1.39	0.84	1.74	4.17	3.94	4.47	5.46	2.55	2.58	2.45	3.13	2.04
	10	2.57	2.81	1.37	0.84	1.53	4.54	4.40	5.00	5.01	2.64	2.88	2.78	3.43	3.05
	20	2.55	2.71	1.38	0.86	1.62	4.94	4.14	5.36	4.27	2.77	2.68	2.82	3.63	2.71
	30	2.16	2.54	1.31	0.93	1.82	5.41	3.83	5.12	4.83	2.79	3.18	2.79	3.60	2.90
	Mean	2.40	2.69	1.36	0.86	1.68	4.76	4.08	4.99	4.89	2.69	2.83	2.71	3.45	2.67
Low	0	2.38	2.76	1.19	0.88	1.68	2.20	3.89	5.06	4.28	2.56	2.95	2.40	3.97	3.35
	10	2.33	3.43	1.26	0.86	1.36	3.94	4.45	5.12	5.09	2.70	3.16	2.87	4.00	3.58
	20	2.39	2.91	1.20	0.91	1.37	3.62	3.86	6.06	3.80	2.97	3.91	3.14	4.13	3.50
	30	2.93	3.24	1.22	0.92	1.52	3.37	4.33	6.38	4.09	3.33	3.66	2.93	4.17	3.66
	Mean	2.51	3.09	1.22	0.89	1.48	3.28	4.13	5.66	4.31	2.89	3.42	2.84	4.07	3.52
High	0	2.46	3.20	1.30	0.89	1.89	2.83	4.03	4.77	4.99	3.27	3.15	3.07	3.77	2.47
	10	2.47	3.05	1.33	0.94	1.86	3.30	4.26	5.17	4.89	2.92	3.27	2.97	4.43	3.09
	20	2.32	2.05	1.42	0.89	1.83	3.42	4.52	5.22	4.52	3.17	3.09	3.12	4.03	3.31
	30	2.96	2.99	1.37	0.82	1.78	3.42	4.31	5.72	5.74	3.34	3.46	2.92	4.33	3.06
	Mean	2.55	2.94	1.35	0.88	1.84	3.24	4.36	5.22	5.04	3.18	3.24	3.02	4.13	2.98
								Statistical significance ($P > F$)							
Manure		0.89§	0.13	0.25	0.62	0.31	0.01	0.87	0.61	0.48	0.38	0.07	0.01	0.01	0.14
Fertilizer		0.11	0.21	0.93	0.92	0.43	0.11	0.09	0.01	0.13	0.26	0.09	0.19	0.11	0.25

† Sites 1b to 6b, and 8b, soybean; 7b, 9b, and 11b to 16b, corn.

‡ No fertilizer application in second year.

§ A manure by P fertilizer interaction was observed at Sites 1b ($P \leq 0.05$).

Table 11. Plant P concentration of second-year corn and soybean and a second application of P fertilizer.

Manure rate	Fertilizer rate	Sites†													
		1b‡	2b	3b	4b	6b	7b	8b	9b	11b‡	12b‡	13b	14b	15b	16b
	kg P ha^{-1}							g P kg^{-1}							
Control	0	3.22	2.92	3.00	3.56	2.98	3.21	2.64	4.59	3.92	4.23	3.49	3.91	3.74	4.15
	10	3.14	2.82	3.09	3.56	2.96	3.42	2.68	5.22	3.79	4.05	3.60	4.03	3.74	4.16
	20	3.19	2.96	3.30	3.78	3.33	3.83	2.88	5.01	3.78	4.15	3.83	4.10	3.93	4.20
	30	3.15	3.02	3.21	3.80	3.43	3.66	2.89	5.12	3.87	4.10	3.88	4.07	3.81	4.34
	Mean	3.17	2.93	3.15	3.67	3.18	3.53	2.77	4.99	3.84	4.13	3.70	4.03	3.80	4.21
Low	0	3.16	3.08	3.32	3.63	3.37	2.78	2.68	5.23	3.85	4.29	3.87	3.99	4.13	4.24
	10	3.18	3.02	3.19	3.75	3.32	3.42	2.76	5.47	3.87	4.18	3.67	4.18	3.67	4.28
	20	3.27	2.95	3.25	3.61	3.30	3.38	2.86	4.87	3.96	4.13	3.68	4.10	3.80	4.03
	30	3.25	3.02	3.24	4.00	3.21	3.36	2.82	4.93	3.71	4.19	3.79	4.11	3.77	4.37
	Mean	3.22	3.02	3.25	3.75	3.30	3.24	2.78	5.13	3.85	4.20	3.75	4.09	3.84	4.23
High	0	3.21	2.98	3.50	3.85	3.03	2.70	2.78	5.10	4.08	3.73	3.72	4.14	3.82	3.67
	10	3.36	2.96	3.27	3.71	3.30	2.42	2.80	5.15	4.02	4.03	3.96	4.00	3.91	4.20
	20	3.29	3.02	3.39	3.98	3.23	3.07	2.75	4.99	4.03	3.92	4.01	4.15	3.68	3.83
	30	3.27	2.82	3.35	3.81	3.34	3.00	3.05	5.14	4.00	4.04	3.93	3.85	4.14	4.11
	Mean	3.28	2.94	3.38	3.84	3.23	2.80	2.87	5.10	4.03	3.93	3.90	4.04	3.89	3.95
								Statistical significance ($P > F$)							
Manure		0.92	0.59	0.29§	0.02	0.89	0.15	0.43	0.41	0.21	0.04	0.07§	0.82	0.26§	0.55
Fertilizer		0.81	0.86	0.23	0.07	0.11	0.02	0.01	0.65	0.63	0.99	0.25	0.74	0.39	0.03

† Sites 1b to 6b, and 8b, soybean; 7b, 9b, and 11b to 16b, corn.

‡ No fertilizer application on second year.

§ A manure by P fertilizer interaction was observed at Sites 3b, 13b, and 15b ($P \leq 0.05$).

Table 12. Plant P uptake of second-year corn and soybean and a second application of P fertilizer.

Manure rate	Fertilizer rate	Sites† 1b‡	2b	3b	4b	6b	7b	8b	9b	11b‡	12b‡	13b	14b	15b	16b
	kg P ha^{-1}							mg P pl^{-1}							
Control	0	7.57	7.98	4.26	2.98	5.21	13.67	10.38	21.20	21.58	10.79	9.00	9.55	11.83	8.48
	10	8.10	7.97	4.30	2.97	4.89	15.51	11.74	26.13	19.10	10.66	10.34	11.21	12.78	12.76
	20	8.24	8.05	4.65	3.25	5.45	18.83	11.95	27.19	16.32	11.44	10.28	11.56	14.28	11.42
	30	6.78	7.73	4.25	3.51	6.31	19.88	11.08	26.33	18.78	11.53	12.24	11.36	13.75	12.57
	Mean	7.67	7.93	4.36	3.18	5.46	16.97	11.29	25.21	18.95	11.10	10.47	10.92	13.16	11.31
Low	0	7.78	8.43	4.00	3.19	5.66	6.17	10.41	27.19	16.34	10.89	11.48	9.57	16.33	14.43
	10	7.71	10.38	4.06	3.22	4.55	13.77	12.21	28.25	19.71	11.27	11.61	12.06	14.64	15.69
	20	8.16	8.60	3.91	3.27	4.67	12.28	10.99	29.73	15.05	12.28	14.41	12.92	15.84	14.24
	30	9.78	9.80	4.01	3.69	4.96	11.97	12.04	31.62	15.15	13.80	13.93	12.02	15.72	16.18
	Mean	8.36	9.30	3.99	3.34	4.96	11.05	11.41	29.2	16.56	12.06	12.86	11.64	15.63	15.13
High	0	7.87	9.55	4.58	3.41	5.65	7.65	11.10	24.40	20.42	12.18	11.72	12.77	14.33	9.10
	10	8.34	9.03	4.46	3.47	6.14	8.95	11.95	26.50	19.63	11.79	12.94	11.91	17.30	13.15
	20	7.78	7.55	4.92	3.54	5.90	10.84	12.41	25.96	18.33	12.3	12.49	12.99	14.83	12.77
	30	9.69	8.42	4.77	3.14	5.94	10.38	13.07	28.96	23.12	13.58	13.58	11.31	18.00	12.51
	Mean	8.42	8.64	4.68	3.39	5.91	9.46	12.48	26.45	20.37	12.46	12.68	12.25	16.11	11.88
							Statistical significance ($P > F$)								
Manure		0.83§	0.18	0.12	0.18	0.60	0.03	0.70§	0.65	0.44	0.55	0.05	0.14	0.01	0.29
Fertilizer		0.16	0.32	0.81	0.29	0.82	0.06	0.01	0.01	0.18	0.24	0.09	0.21	0.26	0.18

† Sites 1b to 6b, and 8b, soybean; 7b, 9b, and 11b to 16b, corn.

‡No fertilizer application on second year.

§ A manure by P fertilizer interaction was observed at Sites 1b and 8b ($P \leq 0.05$).

Table 13. Grain yield of second-year corn and soybean and a second application of P fertilizer.

Manure rate	Fertilizer rate	Sites†													
		1b‡	2b	3b	4b	6b	7b	8b	9b	11b‡	12b‡	13b	14b	15b	16b
	kg P ha^{-1}	Mg kg^{-1}													
Control	0	2.31	2.84	2.91	3.91	2.39	9.64	2.64	7.96	13.38	8.58	10.50	13.93	10.88	12.94
	10	2.31	3.29	3.14	4.01	2.57	9.97	2.58	7.87	12.43	9.46	10.36	12.91	11.17	13.26
	20	2.38	2.69	3.10	3.78	2.50	10.17	2.73	8.65	11.73	8.66	10.41	12.98	11.11	11.59
	30	2.48	3.05	3.09	3.98	2.37	9.30	2.64	7.10	13.35	9.20	10.51	13.97	10.61	11.45
	Mean	2.37	2.97	3.06	3.92	2.46	9.77	2.65	7.90	12.72	8.97	10.44	13.45	10.94	12.31
Low	0	2.22	3.57	2.96	3.99	2.22	9.80	2.75	8.69	13.53	9.46	10.26	12.90	11.20	13.16
	10	2.29	4.11	3.27	3.92	2.47	10.17	2.69	8.17	13.17	9.39	10.70	13.47	11.00	14.27
	20	2.14	3.60	2.95	3.85	2.56	9.87	2.53	7.86	13.19	9.02	10.51	14.59	11.05	14.15
	30	2.24	4.20	3.23	3.78	2.51	9.99	2.86	8.69	13.01	8.74	10.61	13.84	11.14	12.92
	Mean	2.22	3.87	3.10	3.89	2.44	9.96	2.70	8.35	13.23	9.15	10.52	13.70	11.10	13.63
High	0	2.43	3.96	3.29	3.87	2.47	9.66	2.64	6.98	12.94	9.33	10.90	13.48	11.13	13.53
	10	2.56	4.08	3.23	3.89	2.49	9.77	2.73	6.66	12.83	9.28	11.12	13.73	11.63	14.12
	20	2.50	4.00	3.09	3.90	2.57	9.72	2.68	6.45	12.80	9.88	10.89	13.32	11.61	13.86
	30	2.56	4.01	3.32	3.81	2.70	9.97	2.69	7.38	13.35	10.53	10.92	12.96	11.32	13.65
	Mean	2.51	4.01	3.23	3.87	2.56	9.78	2.70	6.87	12.98	9.75	10.96	13.37	11.42	13.79
		Statistical significance ($P > F$)§													
Manure		0.58	0.23	0.48	0.16	0.91	0.88	0.91	0.23	0.60	0.35	0.09	0.53	0.16	0.15
Fertilizer		0.51	0.22	0.04	0.21	0.12	0.77	0.71	0.78	0.40	0.85	0.91	0.94	0.52	0.48

† Sites 1b to 6b, and 8b, soybean; 7b, 9b, and 11b to 16b, corn.

‡ No fertilizer application on second year.

§ No manure by P fertilizer interaction was observed at any site ($P \leq 0.05$).

Table 14. Grain P concentration of second-year corn and soybean and a second application of P fertilizer.

Manure rate	Fertilizer rate	Sites†													
		1b‡	2b	3b	4b	6b	7b	8b	9b	11b‡	12b‡	13b	14b	15b	16b
	kg P ha^{-1}	g P kg^{-1}													
Control	0	5.05	6.26	5.84	6.42	4.66	2.19	4.91	2.03	2.48	2.40	1.81	2.22	1.87	2.35
	10	4.92	6.16	5.86	6.51	4.79	2.03	5.24	2.28	2.63	2.37	2.41	2.09	2.49	2.49
	20	4.89	6.78	5.89	6.39	4.89	2.16	5.53	2.21	2.69	2.86	2.25	2.18	2.08	2.37
	30	4.93	6.17	5.82	6.42	5.47	2.29	5.11	2.25	2.38	2.56	2.36	2.14	2.65	2.00
	Mean	4.95	6.34	5.85	6.44	4.95	2.17	5.20	2.19	2.55	2.54	2.21	2.16	2.27	2.30
Low	0	5.07	6.01	5.37	6.31	4.76	2.48	5.65	2.21	2.35	2.41	2.01	2.17	2.18	2.68
	10	5.07	6.30	6.05	6.47	5.03	2.41	5.29	2.00	2.71	2.53	2.12	2.36	2.41	2.15
	20	5.08	6.21	5.12	6.11	4.95	2.76	5.59	2.30	2.62	2.33	2.24	2.24	2.21	2.20
	30	5.21	6.63	5.30	6.28	5.01	2.15	4.99	2.07	2.77	2.53	2.27	2.04	2.33	2.03
	Mean	5.11	6.29	5.46	6.29	4.94	2.45	5.38	2.15	2.61	2.45	2.16	2.20	2.28	2.27
High	0	5.28	6.13	5.91	6.56	5.09	2.08	5.13	2.19	2.61	2.46	2.15	2.39	2.18	2.53
	10	5.30	6.40	6.07	6.91	4.78	2.27	5.34	2.33	2.76	2.56	2.32	2.44	2.16	2.43
	20	5.19	6.36	5.58	6.46	4.97	2.58	5.13	2.39	2.70	2.54	2.37	1.82	2.10	2.63
	30	5.34	6.55	5.72	6.85	4.92	2.40	5.37	2.58	2.71	2.67	2.27	2.10	2.43	2.21
	Mean	5.28	6.36	5.82	6.70	4.94	2.33	5.28	2.37	2.70	2.56	2.28	2.19	2.22	2.45
		Statistical significance ($P > F$)§													
Manure		0.05	0.94	0.24	0.35	0.99	0.24	0.37	0.29	0.59	0.23	0.25	0.86	0.89	0.59
Fertilizer		0.41	0.19	0.25	0.71	0.11	0.16	0.41	0.32	0.09	0.43	0.01	0.18	0.14	0.06

† Sites 1b to 6b, and 8b, soybean; 7b, 9b, and 11b to 16b, corn.

‡ No fertilizer application on second year.

§ No manure by P fertilizer interaction was observed at any site ($P \leq 0.05$).

Table 15. Grain P removal of second-year corn and soybean and a second application of P fertilizer.

Manure rate	Fertilizer rate	Sites†													
		1b‡	2b	3b	4b	6b	7b	8b	9b	11b‡	12b‡	13b	14b	15b	16b
	kg P ha^{-1}	kg P ha^{-1}													
Control	0	11.7	17.8	17.0	25.1	11.4	21.0	12.8	16.8	33.1	20.6	19.1	31.2	20.4	30.0
	10	11.4	20.4	18.5	26.1	12.4	20.1	13.5	18.3	33.0	22.5	24.9	27.0	27.9	32.9
	20	11.7	18.3	18.2	24.2	12.4	21.6	14.8	19.3	31.7	24.9	23.5	28.2	23.1	27.5
	30	12.3	18.9	18.0	25.6	13.0	21.3	13.4	15.8	32.0	23.6	24.8	29.9	28.2	23.1
	Mean	11.8	18.9	17.9	25.2	12.3	21.1	13.6	17.5	32.5	22.9	23.1	29.1	24.9	28.4
Low	0	11.2	21.2	16.0	25.2	10.5	24.3	15.4	19.2	31.9	22.9	20.6	28.0	24.4	35.1
	10	11.5	25.9	19.4	25.4	12.4	24.4	14.2	16.1	35.6	23.8	22.8	31.8	26.5	31.3
	20	9.7	22.3	15.0	23.5	12.7	27.2	14.1	18.0	34.6	21.1	23.5	32.6	24.4	31.2
	30	11.6	27.6	17.1	23.8	12.6	21.5	14.1	17.9	36.0	22.1	24.1	28.1	25.9	26.3
	Mean	11.0	24.2	16.8	24.5	12.1	24.4	14.4	17.8	34.5	22.5	22.8	30.1	25.3	31.0
High	0	12.9	24.3	19.4	25.4	12.5	20.1	13.5	15.1	33.9	23.1	23.4	32.0	24.2	34.8
	10	13.6	26.1	19.5	26.7	11.9	22.3	14.5	15.5	35.4	23.7	25.7	33.5	25.1	34.6
	20	13.0	25.5	17.3	25.2	12.8	25.2	13.7	15.5	34.6	25.0	25.8	24.3	24.4	36.4
	30	13.6	26.2	19.0	26.1	13.3	23.9	14.3	19.2	36.2	28.1	24.9	27.2	27.5	30.3
	Mean	13.3	25.5	18.8	25.9	12.6	22.9	14.2	16.3	35.0	25.0	24.9	29.3	25.3	34.0
		Statistical significance (P > F)§													
Manure		0.41	0.23	0.37	0.35	0.95	0.30	0.55	0.69	0.64	0.34	0.12	0.53	0.96	0.40
Fertilizer		0.47	0.08	0.07	0.42	0.03	0.10	0.94	0.78	0.57	0.57	0.01	0.40	0.20	0.06

† Sites 1b to 6b, and 8b, soybean; 7b, 9b, and 11b to 16b, corn.

‡ No fertilizer application on second year

§ No manure by P fertilizer interaction was observed at any site ($P \leq 0.05$).

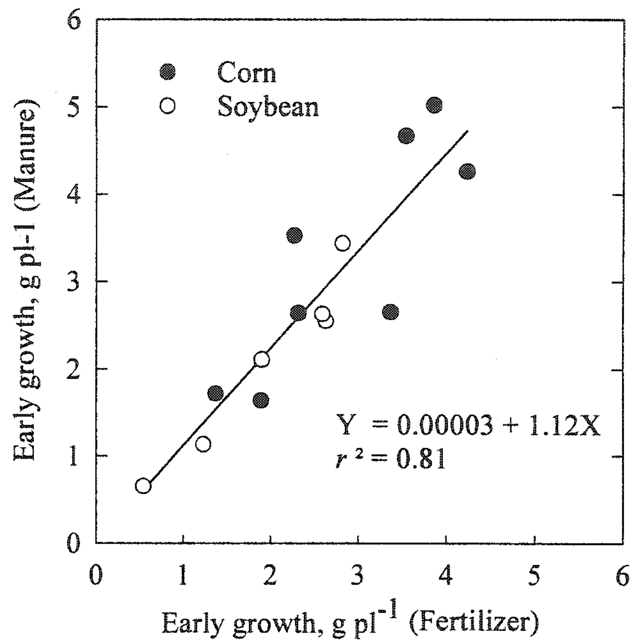

Figure 1. Early growth with fertilizer and manure application at similar P rates. Data for eight corn sites and six soybean sites. Sites 3 and 15 were not included.

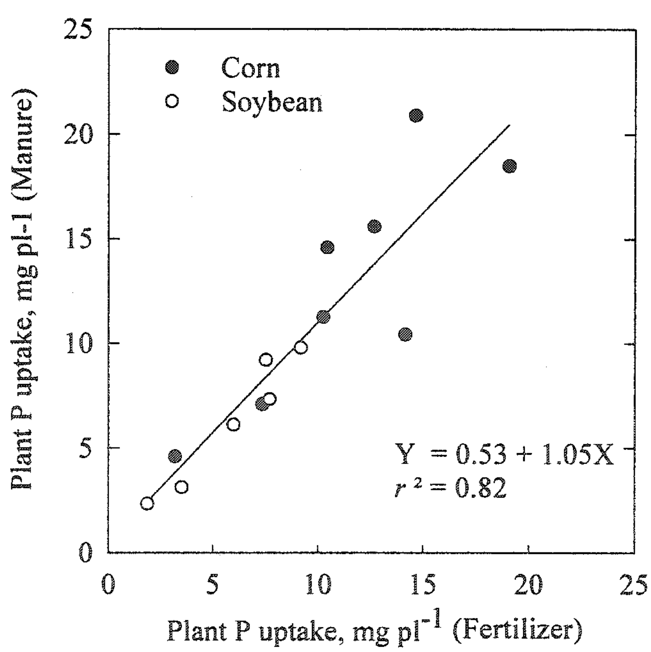

Figure 2. Plant P uptake with fertilizer and manure application at similar P rates. Data for eight corn sites and six soybean sites. Sites 3 and 15 were not included.

CHAPTER 3. EFFECT OF LIQUID SWINE MANURE APPLICATION FOR CORN-SOYBEAN ROTATIONS ON SOIL PHOSPHORUS USING ROUTINE AND ENVIRONMENTAL SOIL TESTS

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ABSTRACT

Manure phosphorus management is a concern in many areas where livestock production has concentrated. This study compared the effects of liquid swine (*Sus scrofa domesticus*) manure and P fertilizer application on soil test P (STP) using three routine P tests - Bray-1 P (BP), Olsen (OP), and Mehlich-3 (M3P) - and two environmental tests - water extraction (WP) and Fe-oxide filter paper (FeP) test - under crop production conditions. Sixteen field trials were conducted across Iowa on soils that tested low (8-15 mg P kg^{-1}) to very high (>30 mg P kg^{-1}) as measured by BP. Manure application rates varied from 17 to 99 kg P ha^{-1} and fertilizer rates varied from 0 to 30 kg P ha^{-1}. Treatment effects on STP were evaluated during two consecutive years. Soil samples were collected before initial treatment application and after harvesting each crop. Manure or fertilizer P increased STP in many sites, and soil tests did not differ consistently in detecting an STP increase due to manure and fertilizer P. Relationships between soil P extracted by the tests were similar for unmanured, manured, or fertilized soils, and correlation coefficients were >0.87 (correlations were lowest for WP). Differences between both P sources in increasing STP were not evident when similar rates of P were compared. Routine and environmental P tests did not differ in assessing available P from liquid swine manure or fertilized soils.

INTRODUCTION

Sustainable utilization of animal manure in agricultural systems implies profitable animal and crop production while maintaining or improving soil, water, and air quality. Animal manure provides P needed for crop production, but there is uncertainty in the amount of P that an application of manure can supply for crops. Very high variability in manure P concentration and the proportion of manure P that becomes available for crops are frequent causes of uncertainty for deciding among a variety of possible manure and fertilizer management practices. A recent Iowa survey (Lorimor and Kohl, 1999) showed that the concentration of P in liquid swine manure sources ranged from 0.1 to 6.6 g of P L^{-1}. Iowa manure management guidelines suggest producers to assume that 60% of total P in animal manure is available for crops during the first year of application (Killorn and Lorimor, 1999), but recommended value ranges from 40 to 100% across the North Central region [J. Peters, 2004, unpublished, report to the North Central Region Soil Testing Committee (NCR-13)]. Uncertainty usually results in application of higher amounts of manure than actually are needed by crops. Excessive manure application rates can result in a significant buildup of P in soils (King et al., 1990; Vivekanandan and Fixen, 1990; Sharpley et al., 1993; Sharpley et al., 1994; Lucero et al., 1995; McDowell et al., 2001). For example, King et al., (1990) reported that available soil P measure by routine soil tests increased 10 times in the 0- to 15-cm soil depth when manure rates of 900 kg P ha^{-1} were applied for 11 years. Furthermore, manure application rates that supply needed N for crops often result in a soil P buildup because the P:N ratios in manure often are significantly higher than ratios needed by crops (Heathwaite et al., 2000).

Many studies comparing fertilizer and manure P effects on soil P were conducted under laboratory or greenhouse conditions by measuring soil P with different soil tests (Sharpley and Sisak, 1997; Griffin et al., 2003; Laboski and Lamb, 2003; Siddique and Robinson, 2003; Leytem et al., 2004). For example, Griffin et al. (2003) found that commercial P fertilizer was more efficient than several types of manure in increasing rapidly available P pools measured with $CaCl_2$ and Mehlich-3 (M3P) tests. Manure P sources effects were greater in the modified Morgan test. They suggested that the impact of manure and fertilizer P on soil P is different because P from these sources contribute to different soil P pools as defined by Mattinly (1974): P in solution, labile P, and crystalline P. However, results of studies by Laboski and Lamb (2003) and Siddique and Robinson (2003) indicated that liquid manure P can be more available than P from inorganic fertilizer, presumably because organic acids from manure decomposition reduce soil P sorption.

In many laboratory studies manure and fertilizer P application rates have been applied at rates higher rates than commonly used agronomic rates. Furthermore, published field studies using common management practices and P rates to meet crop nutrient requirements are scarce (Eghball and Power, 1999; Matsi et al., 2003; Atia and Mallarino, 2002). Eghball and Power (1999) evaluated the effects of P- and N-based cattle manure application to corn on soil P levels, with P rates that ranged from 8 to 144 kg P ha^{-1}. They found that the soil available P (measured by Bray-1) was significantly lower when manure or compost were applied based on P crop needs than on N crop needs. Matsi et al., (2003) found that soil available P (measured by Olsen) increased when about 26 kg P ha^{-1} as liquid dairy cattle manure were applied during 4 years to winter wheat. Atia and Mallarino (2002) applied liquid swine manure P rates that ranged from 7 to 123 kg P ha^{-1} and found significant increase in soil test P (STP) with the higher manure rates.

Soil P tests used in production agriculture are based on chemical extractants that dissolve soil P and are supposed to estimate plant-available soil P. The Bray-1 test (BP) proposed by Bray and Kurtz (1945), Olsen test proposed by Olsen et al. (1954), and M3P test proposed by Mehlich (1984) are the most widely used tests in the USA. In Iowa, the OP and M3P are recommended across all soils while BP is recommended in soils with pH <7.3 (Mallarino, 1997; Sawyer et al., 2002). A number of investigators have reported evidence either from greenhouse (Eik et al., 1961; Smith and

Pesek, 1962) or field trials (Mallarino and Blackmer, 1992; Mallarino, 1997; Mallarino, 2003) of underestimation of available P by BP in Iowa's soils with high-pH, $CaCO_3$-affected soils. Much attention has been devoted in recent years to measure soil P that is available for algae growth in aquatic environments and that can be delivered to water resources by erosion, surface runoff or subsurface drainage. For example, it is being argued that the acid extractant of BP or M3P tests likely dissolve phosphates that may not be readily available for algal uptake (Sharpley, 1993; Pote et al, 1996). New tests, or modifications of existing tests have been proposed and often are referred to as "bioavalable" or "environmental" soil P tests (Sharpley, 1993; Pote et al, 1996; Sharpley, 1996; Magdoff et al., 1999; Sharpley and Moyer, 2000). Various versions of a method based on Fe-oxide or Fe-Al-oxides impregnated filter paper (Menon et al., 1989; Sharpley, 1993; Chardon, 2000) use a sink approach to extract weakly bound P. A test based on P extraction with dionized water (Pote et al., 1996) is being used to estimate soil P that may be desorbed from soil during rain and that can be transported as dissolved P to surface or underground water resources. Previous research has shown inconclusive indication of the capacity of these tests to assess effects of various fertilizer and manure P sources on extractable soil P compared with routine P tests commonly used in production agriculture (Magdoff et al., 1999; Atia and Mallarino, 2002).

The objectives of this study were to (i) evaluate the impacts of liquid swine manure and fertilizer P application for corn-soybean rotations on STP and (ii) study how three routine P tests and two environmental P assess the effect of manure or fertilizer P application on extractable soil P under field production conditions.

MATERIALS AND METHODS

Soil samples for this study were collected from plots of 16 field trials involving liquid swine manure and P fertilizer application for corn and soybean conducted in Iowa from 2000 through 2002.

Fourteen of these trials were evaluated for a second year to study residual effects of manure P on a following crop. Trials were established on farmers' fields and soil and crop management practices, except for N, P, and K fertilization, where those used by each farmer. The fields were managed with corn-soybean rotations, except in Site 4a where alfalfa was the previous crop. A rotation of corn and soybean was used in the 14 sites that were evaluated for 2 years, except in Sites 7 and 9 where corn was planted after corn. Table 1 contains information about soil series for the trials and selected chemical properties of the soils measured before treatment application.

Detailed information about treatments and both crop and soil management practices for these trials were provided before together with results of treatment effects on early plant growth and P uptake, grain yield, and P removal in harvested grain (Barbazán and Mallarino, 2004, Chapter 2 of this Dissertation). Briefly, treatments were application rates of liquid swine manure and P fertilizer that were arranged in randomized, complete-block split-plot design with three to four replications. The manure treatments were a control and two to three manure rates ranging from 17 to 99 kg P ha^{-1} across sites. Table 1 shows information about manure application method and rates. Manure application rates for corn were intended to supply 75 kg N ha^{-1} or 150 kg N ha^{-1} based on total manure N. The manure rates applied before soybean were intended to supply approximately one-half (100 kg N ha^{-1}) or total (200 kg N ha^{-1}) expected average N removal with grain harvest. The manure was collected from underground storage pits in farms near each site, and was applied in fall (November) before snow or soils froze or in spring (April or May) three to four wk before planting crops. The manure plots were at least 40 m in length and width varied from 7.5 to 13.5 m according to the width of the commercial applicator used and the crop planter size. The manure was injected to a depth of 10-15 cm or was broadcast and incorporating into the soil by chisel plowing and/or disking using applicators calibrated in the field before applying the treatments. The P fertilizer treatments were applied to subplots measuring 12 m in length and a width that accommodated four or six crop rows depending on planter sizes and row spacing (76 or 97 cm). The fertilizer rates were 0, 10, 20, and 30 kg P ha^{-1} (triple superphosphate) broadcast by hand in spring and incorporated by disking. For second-year crops at 14 sites, manure treatments were not reapplied but fertilizer P treatments were reapplied, except for the second-year of experiments established in 2000.

Initial composite soil samples (12 cores) were collected in spring from a 0 to 15-cm depth from each large plot and replication before applying the treatments. Composite soil samples (12 cores) also were collected from each subplot immediately after harvesting the first and second crops and before fall chisel-plow and disk tillage. Samples were dried at 30 to 40 °C, crushed to pass a 2-mm sieve and analyzed for P, K, pH, and organic matter. Soil P was analyzed in all samples with three routine tests and two environmental tests. The routine tests were BP, OP, and M3P, and procedures followed those described by (Frank et al., 1998). Briefly, Bray-1 P was analyzed by shaking 1 g of dried soil with 10 mL of 0.03M NH_4F + 0.025M HCl for 5 min. Olsen P was analyzed by shaking 1 g of dried soil with 20 mL of 0.5M $NaHCO_3$ buffered pH 8.5 for 30 min. Mehlich-3 P was analyzed by shaking 1 g of dried soil with 10 mL of 0.2M CH_3COOH + 0.25M NH_4NO_3 + 0.015M NH_4F + 0.013M HNO_3 + 0.001M EDTA for 5 min. All extracts were filtered through Whatman No. 42 filter paper and P was measured with the molybdenum-blue - ascorbic acid colorimetric method (Murphy and Riley, 1962). The two environmental P tests were Fe-oxide impregnated filter paper (FeO) and water extractable P (WP). Procedures for the FeP test were those described by Chardon (2000). Briefly, Fe-oxide impregnated filter paper was prepared by immersing paper discs (15-cm diameter, Whatman No. 50) in a solution containing $FeCl_3.6H_2O$, removing discs, letting them dry at room temperature, immersing them in a 2.7-M NH_4OH solution to convert $FeCl_3$ to Fe-oxide, and letting them dry at room temperature. Soil P was extracted by shaking 1 g of dried soil and one paper disc in 30 mL of 0.01M $CaCl_2$ for 16 h, removing the disc, rinsing free of adhered soil particles with deionized water, letting them dry at room temperature, and removing adsorbed P by shaking discs in 40 mL of 0.1M H_2SO_4 for 1 h. The procedure used for WP was described by Pote et al., (1996), and consisted on shaking 1.0 g of soil in 25 mL H_2O for 1 h, centrifuging, and filtering through Whatman No. 42 filter paper. Phosphorus in all extracts was measured with the same colorimetric method used for routine tests (Murphy and Riley, 1962). Soil-test K was measured with the ammonium-acetate test and pH was measured using a 1:1 soil:water ratio following procedures recommended for the North Central Region (Brown, 1998). Soil organic matter was measured with a combustion method (Wang and Anderson, 1998).

Analysis of variance for a randomized, complete-block split plot design was used to assess the effect of manure and fertilizer treatments and their interactions on soil P measurements using the GLM procedure of SAS (SAS Institute, 2000) assuming fixed effects. When the analysis of variance indicated that manure application, P fertilization, or their interaction was significant ($P \leq 0.05$) treatment mean differences were tested by orthogonal comparisons. Orthogonal comparisons for manure were control versus the average of the manure rates and low rate versus high rate (or the mean of the low high rates for a site where three manure rates were applied). The orthogonal comparison for the P fertilizer treatments was the linear effect for rates ranging from 0 to 30 kg P ha^{-1}. The sums of squares of the interaction were partitioned to assess the response to fertilizer for each manure rate and response to manure when no P fertilizer was applied. Regression and correlation analyses were conducted using the REG and CORR procedures of SAS to study relationships between selected measurements.

RESULTS AND DISCUSSION

Treatment Effects on Soil-Test Phosphorus Measured After Harvesting First-Year Crops

Appropriate interpretations of results of manure and fertilizer P effects on soil P requires a study of initial STP variation within and across sites and variation in manure rate applied across sites. As expected, the manure total P concentration varied greatly across sites (Table 1). Total P concentrations ranged from 0.9 to 2.8 g P L^{-1}, which is a range consistent with concentration ranges reported for liquid swine manure sources surveyed in Iowa (Lorimor and Kohl, 1999; Killorn et al., 2000). Although the P fertilizer rates were similar for all sites, the rates of manure differed (Table 1) mainly because the manure rates often were defined based on N crop needs or removal and because the P concentration of the manure actually applied differed from the P concentration of preliminary samples. Therefore, manure P effects on soil P across sites should be expected to differ even if initial STP values had been similar. The soils before treatment application also differed markedly in STP as measured by BP (Table 2). According to Iowa interpretation class for BP (Sawyer et al., 2002) five sites were low (Sites 1, 5, 7, 13, and 14), three were optimum (Sites 4, 9, and 15), and eight others were high or very high (Sites 2, 3, 6, 8, 10, 11, 12, and 16).

Soil-test P variability within each site often was very high, as denoted by SD results from composite soil samples collected from each replication before treatments were applied (Table 2). This high variability should not be surprising mainly for two reasons. First, high STP variability has been described for fields with long histories of manure or fertilizer P application, but especially for manured soils. For example, Mallarino (1996) reported high small-scale spatial STP variability in soils with varied histories of manure and fertilizer application, even within distances smaller than 1m. Atia and Mallarino (2002) found almost as large STP variation as we found when they analyzed samples from plots of research areas as small as 0.4 ha that were selected for uniformity in other soil properties. A second reason is that the width of the manure plots had to be large (from 7.5 m to 13.5 m), so each trial encompassed a large field area. The BP variability sometimes was higher than for OP or M3P, and could be explained by initial pH variation affecting BP results. However, only Sites 3, 6, 11, 13 and 16 had pH >7.3. A number of investigators have reported evidence either from greenhouse (Eik et al., 1961; Smith and Pesek, 1962) and field trials (Mallarino and Blackmer, 1992; Mallarino, 1997; Mallarino, 2003) of underestimation of available P by BP in Iowa's soils with high pH resulting from the presence of $CaCO_3$. Mallarino (1997 and 2003) reported that this problem is more frequent in soils with pH > 7.3.

Table 3 shows effects of manure and fertilizer P on STP measured with BP on samples collected after harvesting the first crop after applying treatments. Manure application increased ($P \leq 0.05$) STP across all fertilizer rates at three sites (Sites 4, 12 and 15), and a significant manure by P fertilizer interaction indicated at least the high rate also increased STP at low P fertilizer rates at five other sites (Sites 7, 8, 9,13, and 14). Fertilizer P application increased STP across all manure treatments at 10 sites (Sites 1, 5 through 10, and 12 through 14). The P fertilizer effect always was linear, and in some sites there was a significant interaction with manure usually indicating inconsistent different STP increases for the manure rates. Li and Barber (1988) and Vivekanandan and Fixen (1990) also found linear STP increases when fertilizer or manure were applied to soils at various uniformly spaced rates. A lack of a significant interaction between manure and P fertilizer at most sites and inconsistent or difficult to explain at a few sites indicate that the effect of either source in increasing STP was independent of the application rate of the other. Some researchers (Swenson, et al., 1949; Sample et al., 1980; Sharpley et al., 1984; Reddy et al., 1999; Laboski and Lamb, 2003; Siddique and Robinson, 2003) have observed or speculated that the effect of a certain amount of P fertilizer on increasing STP would be greater in manured soils because of organic acids resulting from manure decomposition could reduce P sorption.

Any STP response to the treatments in samples collected after harvesting a crop is the result of treatments adding P before planting crops, P removal with harvest, and measuring the fraction of the P remaining in the soil after harvest that a particular soil test can extract. Data for OP in Table 4 show that manure application increased ($P \leq 0.05$) STP across all fertilizer rates at four sites (Sites 4, 8, 12, and 15), and a significant manure by P fertilizer interaction indicated that manure also increased STP at low P fertilizer rates at two other sites (Sites 5 and 13). Therefore, OP detected an STP increase due to manure in most sites where BP also detected an increase (except Site 5). However, OP failed to detect an STP increase due to manure application in three sites (Sites 7, 9, and 14) where BP detected an increase. Data in Table 5 show that M3P detected a STP increase due to manure in 10 sites, in two more than BP did and four more than OP did. In contrast with results for manured plots, the P tests seldom differed at detecting STP increases from P fertilizer application (only at Site 10, where only BP detected an increase).

The differences between tests at detecting an STP increase from manure application (more frequent for M3P) should be interpreted with caution. There were non-significant manure effects increasing BP and OP values at the additional sites where M3P statistically detected an STP increase. Therefore, it is possible that the sensitivity of statistical tests was influenced by differences in amount of P extracted (slightly larger for M3P than for BP and much lower for OP) and by a different influence of within-site STP variability on the tests. Also, less frequent significant STP increases for manured plots compared with fertilized plots for BP and OP could be the result of the lower efficiency for detecting treatment differences for large plots compared with subplots in split-plot designs. In a split-plot design, subplots (the P fertilizer treatments in this study) likely are more homogenous than large plots (manure treatments) and the degrees of freedom for tests of treatment effects are more numerous for subplots than for the large plots.

A study of STP change calculated as STP after P application and crop harvest minus initial STP is useful for P management planning. However, the usefulness of estimating such a change in our experiments is limited by P fertilizer rates near removal rates or lower, high STP differences across sites, and measurements of initial STP for each manure plot and replication but not from each subplot. Data in Table 6 shows treatment effects on first-year STP change for BP. Results for M3P and OP are not shown because trends mirrored results for BP. The results for the different sites were grouped according to the soil-test interpretation class the initial STP values at each site corresponded to, and means for each group were calculated. This grouping for means calculation and discussion were chosen for three reasons. First, an STP increase would have a different agronomic meaning depending on the initial STP value. Second, it is possible that a certain amount of applied P has a different effect on STP change depending on the initial STP level. Third, there was so much variation in STP that could not be explained other than by large within-site variability or random error that a discussion of mean values for groups of sites is more meaningful. Furthermore, results for two outlier high-testing sites (Sites 8 and 10) were excluded when calculating means for that group. At these sites, obviously the initial composite sample was affected by very high within-site STP variability that was similar for the three tests. No other logical reason can explain a large STP decrease in Site 8 except for the highest manure rate, and no logical reason can explain the very large STP increase in Site 10 for all treatments.

Mean results for groups of sites testing low, optimum, or high indicate that both manure and fertilizer P increased ($P \leq 0.05$) STP and not applying P resulted in very small or no STP change. No significant ($P \leq 0.05$) interaction between manure and P fertilizer indicates, for example, that a certain amount of P fertilizer resulted in a statistically similar STP change independently of the manure rate applied. There was no clear or consistent difference in STP change across groups of soil either. Different outcomes could be expected as a result of various interacting processes that we cannot identify with the methods used. These processes may include decreased P sorption due to increased soil P saturation at high P rates or organic acids from manure decomposition blocking adsorption sites (Swenson, et al., 1949; Sample et al., 1980; Sharpley et al., 1984; Reddy et al., 1999; Laboski and Lamb, 2003; Siddique and Robinson, 2003). Other likely processes include P immobilization or mineralization induced by organic compounds in soil, crop residues, and/or manure.

Calculations of mean BP increase for the highest P fertilizer rate (30 kg P ha^{-1}) for the three groups of sites (Table 7) indicate that this rate resulted in 0.2, 0.3, and 0.3 mg STP kg^{-1} per kg applied P for the low, optimum, and high groups, respectively (data for Sites 8 and 10 were not used). Because the manure rates varied across sites, no perfect match with P fertilizer rates is possible. However, an approximate comparison is possible by selecting the manure rate (low or high) and the P fertilizer rate (either the 20- or 30-kg rates) at each site that most closely matched. A match within 4 kg P ha^{-1} for a 20-kg or 30-kg P rate was possible by excluding Sites 3 and 15, for which even the lowest manure rate was at least 44 kg P ha^{-1}. Data for these two sites, and also for Sites 8 and 10 are shown in Table 6 but were not used for these calculations. These calculations resulted in STP changes of 0.1, 0.8, and 0.1 mg STP kg^{-1} per kg of manure P applied for the low, optimum, and high groups, respectively. The higher value for the group of soils testing optimum seem too high compared with the other two groups, and probably is explained by calculations from only two sites with seemingly too high STP change. Similar calculations for the comparable P fertilizer rates were 0.3, 0.5, and 0.2 mg STP kg^{-1} per kg fertilizer P applied for the low, optimum, and high groups, respectively. When results for the three groups of soils are averaged, the two sources did not differ (mean 0.3 mg STP kg^{-1} per kg P applied).

These estimates of STP change should not be directly used as estimates of potential STP increase due to P application for various reasons. First, this type of information is more reliable when collected over many years, such as results for P fertilizer published by Dodd and Mallarino (2004) for Iowa soils, because of large short-term variability due to many factors. Second, STP change is greatly affected by P removal in harvest products and the rates of 20 or 30 kg P ha^{-1} (depending on the site) used to compare effects of manure or P fertilizer is near the P removed with harvest these experiments. Results of these studies published by Barbazán and Mallarino, 2004

(Chapter 2 of this Dissertation) indicate that the average P removal in grain for these P application rates was 24 kg P ha^{-1}. The gross average STP increase per unit of P applied (manure or fertilizer) calculated for the group of soils testing optimum in this study (mean 0.7 mg STP kg^{-1} per kg P applied) is lower than estimates published by Dodd and Mallarino (2004) for long-term Iowa experiments managed with P fertilizer and corn-soybean rotation in soils initially testing near optimum in STP (1.2 to 1.4 mg STP kg^{-1} per kg P fertilizer applied).

Treatment Effects on Soil-Test Phosphorus After Harvesting Second-Year Crops

Interpretation of treatment effects on STP measured after harvesting the second-year crops should recognize that manure treatments were not reapplied for the second crops but P fertilizer treatments were reapplied except at Sites 1, 11, and 12. Even if the manure rates were equal to the sum of P fertilizer rates applied each year, the results still would not be directly comparable. Therefore, study of residual effects of manure applied for the first crops on STP measured after harvesting the second crops will be emphasized.

Table 7 shows treatment effects on STP measured with BP on samples collected after harvesting the second crops. No manure by P fertilizer interaction was observed at any site, which indicates that any source effect on BP was independent of levels of the other source. Manure application increased STP ($P \leq 0.05$) at same three sites where it increased STP the previous year (Sites 4, 12 and 15). The high manure P rate applied at Sites 12 and 15 were among the highest rates applied across sites and was high enough to offset expected P removal in grain of two crops. However, manure rates as high as for sites 12 and 15 were applied at two other sites (Sites 3 and 6) a no BP increase was detected. As expected, P fertilizer increased BP values at most sites (and linearly) where treatments were reapplied.

Data in Table 8 shows that OP test detected an STP increase due to manure application in the same sites where BP did, although at Site 15 the significance was borderline ($P \leq 0.06$). Data in Table 9 shows that M3P detected an STP increase due to manure at one additional site (Site 1). Similarly to results for BP, no significant interactions manure by P fertilizer were observed for BP or M3P and the reapplied P fertilization treatments usually increased OP and M3P values. Therefore, the P tests were more similar in the second year than in the first year at detecting an STP increase due to manure application, which is a result we cannot explain with certainty.

Table 10 shows BP values for soil samples collected before manure application, after the first crop, and after the second crop along with the 2-year P removal with harvest and the STP change over the 2 years. The outlier data from Site 8 was excluded, as was done for first-year crops before (Table 6), while two sites in Table 6 are not shown here because second-crops could not be evaluated (Sites 5 and 10). Means for the three groups of soils (initially testing low, optimum or high) indicate little or no STP change over 2 years when no manure was applied. The low manure rate (which approximately supplied expected P removal with grain harvest) increased STP 3 to 4 mg P kg^{-1} for the groups of sites testing low and optimum and 8 mg P kg^{-1} for the high-testing group. The range of STP change across sites for the high-testing group was very large indicating very high STP variability. The high manure rate increased STP 5, 8, and 11 mg P kg^{-1} for the groups of sites testing low, optimum, and high, respectively. These results seem to indicate that manure application tended to increase STP more in high-testing soils than in low-testing soils.

Phosphorus Availability after Fertilizer and Manure P Application

There is interest among producers and scientists in knowing if different soil P tests evaluate differently the effect of manure or fertilizer P applications on estimates of plant available P. Some studies have suggested that different soil P tests can differ at assessing the effect of manure application on STP. Lucero et al. (1998) showed that BP and M3P tests were similar at evaluating soil P after poultry litter applications. Rubaek and Sibbesen (1995) showed similar P levels and variation when a resin-based P extraction and OP tests were used to assess soil P across plots that received fertilizers or liquid manure. Results of P extraction and fractionation laboratory studies of soils that received various types of manure (Sharpley and Smith, 1995; Sharpley, 1996) suggested that acid-based extractants such as the BP and M3P tests might overestimate P availability for crops. These authors based their conclusions on high correlation between the $NaHCO_3$-extractable soil P and FeP and sharp increases of the Ca-bound P fraction after manure application. However, recent research in Iowa (Atia and Mallarino, 2002) found no evidence of differences between BP, M3P, OP, and three environmental P tests in assessing liquid swine manure effects on STP, although the amount of soil P extracted varied greatly among tests. Previous research has suggested that soil P tests can differ at evaluating the effect of manure application on STP, mainly for poultry manure, (Rubaek and Sibbesen, 1995; Sharpley and Smith, 1995; Sharpley, 1996; Lucero et al., 1998) but Iowa research with liquid swine manure indicated no differences for BP, M3P, and OP and various environmental P tests (Atia and Mallarino, 2002).

As expected, the amounts of soil P extracted by the soil tests used in this study varied greatly among tests. The mean amount of P extracted across all sites by the three routine tests was 37, 19, and 42 mg P kg^{-1} for BP, OP, and M3P, respectively. The differences between these tests are within values reported previously for Iowa fertilized fields (Mallarino, 1997 and 2003). Data in the Fig. 1 show relationships between soil P extracted by each routine test (BP, OP, and M3P) from plots that received approximately similar rates of manure or fertilizer P across all sites) for samples collected after harvesting the first-year crops. Data for Sites 3 and 15 were excluded because no fertilizer and manure rate were near enough for this comparison. Data for Site 10 is shown in the figure but was not included in the regressions because it tested much higher than all other sites and would skew the result. The strength of the relationship was strong for the three tests but was weaker for OP (r^2 0.80) than for BP and M3P (r^2 0.87 and 0.88). The linear coefficients of the regressions did not differ ($P < 0.05$) from 1.0 for any test. This result indicates that on average across those sites the three routine tests were similar at detecting effects of manure and fertilizer P application of STP. A coefficient significantly higher than one would indicate that manure P increased STP more than a similar P fertilizer rate. A coefficient smaller than one would indicate the opposite result. This result agrees with field results from Atia and Mallarino (2002). However, our result disagrees with results of a recent incubation study (Laboski and Lamb, 2003) that found greater BP values for liquid swine manure than for P fertilizer both applied at rates equivalent to 144 and 288 kg P ha^{-1}. Perhaps different time and intensity of reaction with the soil or manure source differences explain different results for field and incubation studies.

The mean amount of P extracted across all sites by the two environmental P tests was 25 and 8 mg P kg^{-1} for FeP and WP, respectively. These amounts compare with 37,19, and 42 mg P kg^{-1} for BP, OP, and M3P, respectively. Phosphorus extracted by the FeP was intermediate between OP and BP while WP, as expected, extracted the lowest amount of P. The relative amounts of P extracted from soils of this study for FeP and WP were closely similar to amounts reported by Atia and Mallarino (2002). Relative amounts extracted by OP, BP and FeP agree with results reported by Menon et al. (1988), who showed that FeP and OP extracted similar amount of P from fertilized soils and BP extracted 50 to 100% more P.

Figure 2 shows selected relationships between P extracted by the three routine tests and the two environmental tests for plots that received no P, only manure P, or fertilizer P. Data in the three graphs (Fig. 2 A through C) shows that relationships between tests were not different for plot receiving fertilizer or manure. The regression models and lines shown apply to all plots because testes of differences between linear coefficients for separate relationships (not shown) were not significant at ($P \leq 0.05$). Figure 2A shows that M3P was slightly better correlated with BP than OP was. Regressions excluding the few sites with pH >7.3 (not shown) resulted in slightly better relationships between OP and M3P with BP because BP underestimated available soil P in these sites. This result has been observed before for manured and fertilized soils (Mallarino, 1997; Atia and Mallarino, 2002, Mallarino, 2003). Data in graphs 2B and 2C shows that correlations involving FeP and WP environmental P tests were weaker than for correlations between the routine tests, including the correlation between them. The histories of previous manure and fertilizer P applications for these fields were incomplete, but it is very likely that all fields received both swine manure and fertilizer P in the recent past. However, these data strongly suggest no differences between tests in assessing fertilizer or liquid swine manure effects on soil P.

The relative P extraction by the different tests from plots that received fertilizer or manure P at similar rates also was compared by dividing STP from plots receiving P by STP of control plots separately for samples taken after the first crop harvest from manured and fertilized plots (Table 11). The mean relative amount of P extracted by the three routine tests and the two environmental tests across all sites did not differ either between manured and fertilized plots or between tests ($P \leq 0.05$). The P sources differ only at $P \leq 0.07$, which is explained by slightly higher relative extraction by all tests for the fertilizer source compared with the manure source. Study of results by site indicated that relative amounts of P extracted sometimes differed for the sources of P and the tests, although there was no significant source by test interaction at any site. At six sites the P extraction was higher for fertilizer than for manure and at one site (Site 5) P extraction was higher for manure than for fertilizer. At the other sites results were not significant or statistics were ambiguous (for Site 12) and results were not clear. Study of available soil P and manure properties and manure rates applied at Site 5 did not explain reasons for the difference from other sites. The soil and manure analyses (Table 1) showed data ranges within those observed for the other sites. Study of soil and manure properties and equivalence of the manure and fertilizer rates selected for the six sites where P extraction was higher for fertilizer than for manure showed not obvious or consistent differences from those for sites where no differences were observed. The results for these comparisons coincide with comparisons in previous sections at indicating no differences between P tests in detecting effects of manure or fertilizer sources on STP. The results of these comparisons indicate that in some conditions all tests may measure more P from fertilized plots than from manured but differences were small, could not be explained, and do not agree with other type of comparisons in previous sections. Moreover, a smaller P extraction from manured soils compared with fertilized soils at some sites does not agree with previous results for swine manure in Iowa (Atia and Mallarino, 2002) showing no differences and with results from other states that sometimes show larger BP and M3P values for manured plots (Sharpley and Smith, 1995; Sharpley, 1996).

CONCLUSIONS

Application of manure or fertilizer P increased STP measured after crop harvest in many sites. The BP and M3P routine tests tended to detect manure P effects on STP more frequently than the OP routine test (at eight, ten, and six sites of 16 first-crop sites), but tests were similar at detecting STP increase due to fertilizer P application (at nine or ten sites). Results of regression analysis of STP measured by each test measurements after applying manure or fertilizer P at approximately similar rates showed no differences between manured and fertilized soils. Therefore this study provided no conclusive evidence for differences between tests at detecting STP increase when manure of fertilizer P is applied to soils. Routine and environmental soil P tests assessed similarly plant available P from manured or fertilized soils.

Routine and environmental soil P tests agreed on detecting STP increase either from manure or fertilizer, although the amount of P extracted by the different tests were different. Correlations between soil P extracted by the tests were high and similar for unmanured, manured, or fertilized soils, and correlation coefficients were > 0.87 (correlations were lowest for WP).

The results of this study showed no conclusive evidence to expect differences in STP increase from application of liquid swine manure or fertilizer P measured by various soil P tests. This result, together similar conclusion for effects on early crop growth and grain yield (Barbazán and Mallarino, Chapter 2 of this Dissertation), indicate that the availability of P in liquid swine manure is higher than the fraction proposed in many manure management guidelines.

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Table 1. Field locations, predominant soils series, selected soil chemical properties and manure application information.

		Predominant soil		Soil Tests			Manure application		Total P	Manure rate	
Site	Year	Series	Classification†	pH	STK‡	OM§	Date	Method¶	Conc.	Low	High
					mg	g kg^{-1}			g L^{-1}	...... kg P ha^{-1} ...	
1	2000	Webster Nicollet	T. Endoaquolls A. Hapludoll	6.5	133	53	24	Injected	2.1	23	47
2	2001	Talcot Wadena	T. Haplaquoll T. Haplaquoll	5.2	259	40	29	Injected	1.8	32	63
3	2001	Webster Nicollet	T. Endoaquolls A. Hapludoll	6.2	177	30	26	Injected	2.0	44	74
4	2001	Readlyn	A. Hapludoll	7.3	112	39	27	Injected	1.3	27	54
5	2001	Marcus	T. Haplaquoll	6.0	178	64	15	Incorporated	1.6	17	34
6	2000	Kalona Taintor	T. Haplaquoll T.Argiaquoll	7.0	207	59	10	Injected	2.4	36	68
7	2002	Edina	T. Argialboll	7.0	84	35	05	Injected	1.8	23	53
8	2001	Webster Nicollet	T. Endoaquolls A. Hapludoll	5.5	130	37	12	Injected	0.9	29	42
9	2001	Brownton Otosen	T. Haplaquoll A. Hapludoll	6.0	174	57	21	Injected	1.0	19	37
10	2000	Clarion	T. Hapludoll	6.1	208	49	30	Injected	1.5	20	49
11	2000	Webster Nicollet	T. Endoaquolls A. Hapludoll	6.6	171	58	24	Injected	2.8	28	56
12	2000	Marcus	T. Haplaquoll	6.3	191	63	27	Incorporated	2.3	36	71
13	2001	Marcus	T. Haplaquoll	6.7	164	67	15	Incorporated	1.5	26	51
14	2001	Mehaska Nira	A. Argiudoll T. Hapludoll	6.5	206	40	19	Injected	1.7	33	61
15	2001	Kenyon	T. Hapludoll	6.7	98	38	09	Injected	2.3	49	99
16	2001	Clarion	T. Hapludoll	6.8	130	46	21	Injected	1.2	26	52

† T , Typic; A, Aquic.

‡ STK, soil-test K (1 *M* Amonium acetate) in 0-15cm depth samples taken before treatment application.

§ OM, organic matter.

¶ Manure was injected or broadcast and incorporated within 24 hours.

Table 2. Initial soil test P by Bray-1, Olsen, and Mehlich-3 tests.

Site	Soil test †					
	Bray-1		Olsen		Mehlich-3	
	Mean	SD‡	Mean	SD	Mean	SD
	mg kg^{-1}					
1	14	2	8	1	17	3
2	34	11	15	6	39	13
3	25	14	13	5	36	8
4	19	4	13	3	33	5
5	11	8	7	5	13	11
6	49	58	25	28	54	62
7	11	3	5	1	13	4
8	37	9	15	4	42	11
9	17	9	8	5	19	10
10	89	20	42	11	94	19
11	22	5	13	3	28	5
12	52	6	24	3	53	8
13	11	3	8	2	13	3
14	13	3	8	2	16	3
15	19	4	9	2	20	4
16	28	12	15	7	30	14

† Data from one composite sample collected before applying P treatments from each manure plot and replication.

‡ SD, standard deviation.

Table 3. Effect of manure and fertilizer application on soil-test P extracted by Bray-1 for soil sampling after harvesting the first-year crop at each site.

Manure treatment	Fertilizer rate	Site															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	kg P ha^{-1}	mg P kg^{-1}															
Control	0	15	39	32	31	6	46	15	18	17	98	31	54	12	12	17	29
	10	16	42	32	25	6	54	23	29	28	100	32	63	12	15	13	31
	20	21	49	41	24	8	58	21	29	33	101	28	58	15	16	19	51
	30	18	40	33	32	10	58	19	38	38	107	29	58	18	19	15	49
Low	0	17	37	30	33	9	43	14	24	34	107	21	57	20	14	18	39
	10	21	54	30	29	9	55	18	29	32	125	28	72	17	15	24	31
	20	20	45	37	34	11	66	20	33	37	134	32	72	22	16	22	34
	30	29	53	32	33	17	89	20	33	35	117	29	81	21	18	26	47
High	0	19	48	32	38	16	30	17	25	27	101	33	77	21	17§	28	24
	10	22	56	33	35	26	29	19	38	37	131	36	61	20	20	28	34
	20	20	45	44	30	23	33	24	43	39	122	40	95	23	27	29	25
	30	21	49	39	36	33	35	25	47	47	130	42	93	28	23	33	34
		Statistical significance ($P > F$)															
Manure		0.29	0.81	0.58	0.03	0.24	0.50	0.23†	0.35†	0.23†	0.58	0.15	0.01	0.10†	0.08†	0.01	0.39
Fertilizer		0.02	0.40	0.21	0.30	0.01	0.01	0.01	0.01	0.02	0.05	0.46	0.01	0.05	0.01	0.85	0.32

† Significant manure by P fertilizer interaction ($P \leq 0.05$).

Table 4. Effect of manure and fertilizer application on soil-test P extracted by Olsen for soil sampling after harvesting the first-year crop at each site.

Manure treatment	Fertilizer rate	Site 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	kg P ha^{-1}	mg P kg^{-1}															
Control	0	8	15	15	18	4	22	9	7	9	48	18	25	8	7	10	14
	10	8	17	15	13	3	24	13	12	15	56	18	29	9	7	8	15
	20	11	21	18	14	5	26	13	11	20	49	16	28	10	8	12	27
	30	8	17	15	18	6	25	12	15	21	55	18	27	13	10	10	25
Low	0	9	16	13	19	6	22	9	13	19	58	11	28	13	8	11	21
	10	11	22	13	18	6	26	11	14	16	64	16	34	12	8	15	14
	20	10	18	15	18	8	33	11	22	19	66	18	34	14	8	14	17
	30	16	22	15	18	10	43	12	17	21	63	15	39	15	9	15	21
High	0	10	19	15	23	10	16	10	11§	13§	51	19	39	14	8	18	10
	10	12	22	18	20	15	16	11	16	18	64	20	33	14	9	17	17
	20	10	19	24	16	14	17	14	18	24	63	22	45	14	14	17	12
	30	11	19	19	21	18	19	14	19	26	70	25	45	20	12	19	17
		Statistical significance ($P > F$)															
Manure		0.35	0.83	0.23	0.05	0.17†	0.51	0.31	0.02	0.17	0.70	0.22	0.01†	0.14†	0.23	0.01	0.45
Fertilizer		0.04	0.41	0.12	0.21	0.01	0.01	0.02	0.02	0.01	0.27	0.38	0.05	0.05	0.01	0.94	0.46

† Significant manure by P fertilizer interaction ($P \leq 0.05$).

Table 5. Effect of manure and fertilizer application on soil-test P extracted by Mehlich-3 for soil sampling after harvesting the first-year crop at each site.

Manure treatment	Fertilizer rate	Site 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	kg P ha^{-1}	mg P kg^{-1}															
Control	0	16	42	45	36	7	55	17	17	19	106	40	62	16	14	17	30
	10	20	45	41	27	8	61	25	29	30	109	39	73	16	17	14	38
	20	24	51	52	28	10	71	25	28	33	119	35	67	19	19	19	53
	30	22	43	41	36	12	66	21	38	39	119	38	65	23	21	16	52
Low	0	22	39	38	38	13	53	16	30	35	131	25	67	25	15	19	45
	10	26	59	38	36	10	66	19	33	31	133	32	81	24	16	24	32
	20	24	48	43	39	16	79	21	47	35	141	35	85	29	18	23	39
	30	35	56	41	39	20	106	22	39	35	133	37	90	29	21	30	50
High	0	24	51	46	46	19	36	20	25	28	113	38	85	29	19	31	24
	10	24	58	48	41	33	35	22	40	34	139	38	76	25	22	30	39
	20	25	49	63	31	27	41	27	44	41	124	45	112	30	29	34	29
	30	23	52	52	41	38	44	27	49	47	140	49	107	35	25	38	37
		Statistical significance ($P > F$)															
Manure		0.07†	0.79	0.31	0.04	0.22†	0.49	0.18†	0.02	0.27†	0.61	0.19	0.01†	0.14†	0.10†	0.01	0.48
Fertilizer		0.01	0.47	0.97	0.22	0.01	0.01	0.03	0.01	0.02	0.38	0.39	0.05	0.04	0.01	0.67	0.37

† Significant manure by P fertilizer interaction ($P \leq 0.05$).

Table 6. Changes in soil-test P measured by Bray-1 for soil samples colleted after harvesting the first-year crop minus initial values.

Manure treatment	Fertilizer rate	Sites by soil-test P classes: Low						Optimum				High or very high								
		1	5	7	13	14	Mean	4	9	15	Mean	2	3	6	8	10	11	12	16	Mean
	kg P ha^{-1}	mg P kg^{-1}																		
Control	0	0	-2	4	1	-1	0	11	-5	-5	2	5	5	-4	-22	16	7	-1	-9	0
	10	2	-2	11	0	3	3	6	7	-9	2	8	6	5	-11	18	8	9	-7	4
	20	7	0	10	4	3	5	5	12	4	5	15	14	9	-10	18	4	3	13	8
	30	4	2	8	6	6	5	12	17	-7	8	7	6	9	-2	25	5	3	11	8
	Mean	3	-1	8	3	3	3	8	8	-3	4	9	8	5	-11	19	6	4	2	5
Low		(23)†	(17)	(23)	(26)	(33)		(27)	(19)	(49)		(32)	(44)	(36)	(29)	(20)	(28)	(36)	(26)	
	0	4	-1	2	9	1	3	13	20	2	11	4	4	-6	-12	6	3	4	15	2
	10	6	-2	6	7	2	4	10	17	9	11	21	5	6	-7	23	10	19	7	10
	20	6	1	8	12	2	6	14	22	6	13	12	12	17	-3	33	14	19	10	14
	30	15	6	8	11	5	9	13	20	10	14	20	6	40	-3	16	11	28	23	18
	Mean	8	1	6	10	3	5	13	20	4	12	14	7	14	-6	20	10	17	14	11
High		(47)†	(34)	(53)	(51)	(61)		(54)	(37)	(99)		(63)	(74)	(68)	(42)	(49)	(56)	(71)	(52)	
	0	5	2	7	12	5	10	21	11	11	14	13	10	-20	-9	18	10	30	3	7
	10	7	13	9	11	8	12	18	21	11	17	21	12	-21	4	48	12	14	14	13
	20	6	9	14	14	15	14	14	23	13	16	10	22	-16	9	40	17	48	4	17
	30	7	19	14	18	11	10	19	32	16	22	14	18	-14	12	48	19	46	14	19
	Mean	6	11	11	14	10	10	18	22	13	17	14	15	-18	4	38	14	34	9	14
		Significance ($P > F$)‡																		
Manure		0.22	0.14	0.33	0.14	0.09		0.01	0.13	0.01		0.11	0.36	0.50	0.40	0.61	0.02	0.01	0.46	
Fertilizer		0.02	0.01	0.01	0.05	0.01		0.30	0.01	0.85		0.40	0.21	0.01	0.01	0.08	0.45	0.08	0.32	

† Numbers between parentheses represent manure P rates, kg P ha^{-1}.

‡ No manure by fertilizer interaction was observed at any site ($P \leq 0.05$).

Table 7 . Effect of manure applied before a first crop and fertilizer application on soil-test P extracted by Bray-1 for soil sampling after harvesting second-year crops at each site. Sites 5 and 10 were not evaluated on the second-year.

Manure Treat.	Fertilizer rate†	Site 1	2	3	4	6	7	8	9	11	12	13	14	15	16
	kg P ha^{-1}	mg P kg^{-1}													
Control	0	13	44	24	18	51	15	15	15	27	42	12	14‡	22	20‡
	10	14	49	28	18	58	16	24	20	26	46	15	19	23	34
	20	15	66	34	21	69	20	26	27	20	43	25	21	29	54
	30	13	55	36	23	75	28	29	31	21	41	27	26	33	57
Low	0	12	39	32	20	44	20	20	18	19	48	18	17	27	36
	10	16	62	30	23	60	19	23	22	21	47	23	20	31	28
	20	16	44	35	32	71	20	26	23	26	45	33	20	32	35
	30	20	64	36	31	80	30	33	25	21	56	47	30	46	52
High	0	15	54	32	21	33	15	22	18	30	55	19	19	39	17
	10	18	61	38	26	32	19	32	23	30	51	30	18	35	27
	20	21	57	45	30	35	26	41	30	29	71	40	19	33	34
	30	20	73	42	24	42	29	41	32	33	64	44	23	51	39
		Statistical significance ($P > F$)‡													
Manure		0.07	0.60	0.37	0.02	0.44	0.68	0.14	0.77	0.20	0.02	0.21	0.51	0.02	0.37
Fertilizer		0.06	0.01	0.15	0.02	0.01	0.01	0.01	0.01	0.98	0.52	0.01	0.01	0.01	0.01

† Fertilizer P treatments were reapplied for second-year crops, except at Sites 1, 11, and 12.

‡ No manure by fertilizer interaction was observed at any site ($P \leq 0.05$).

Table 8 . Effect of manure applied before a first crop and fertilizer application on soil-test P extracted by Olsen for soil sampling after harvesting second-year crops at each site. Sites 5 and 10 were not evaluated on the second-year.

Manure	Fertilizer	Site													
Treat.	rate†	1	2	3	4	6	7	8	9	11	12	13	14	15	16
	kg P ha^{-1}	....						mg P kg^{-1}							....
Control	0	6	17	10	11	30	9	6	8	13	21	6	9	13	12
	10	7	19	11	12	31	10	10	11	13	23	8	11	14	21
	20	7	25	15	13	37	11	10	16	9	21	17	12	18	37
	30	6	21	15	15	38	16	12	16	10	21	15	14	20	35
Low	0	6	15	13	13	25	13	10	10	9	23	10	10	17	24
	10	7	23	12	15	35	11	11	12	9	24	13	12	19	17
	20	8	20	15	21	40	13	15	12	12	24	19	12	20	22
	30	10	25	16	20	50	17	15	15	10	30	27	16	27	30
High	0	7	21	17	13	18	9	10	9	16	29	11	10	22	9
	10	9	22	20	16	19	12	14	12	16	27	18	10	20	17
	20	11	20	25	18	19	14	17	16	16	38	23	12	19	20
	30	10	26	19	16	26	18	17	16	17	32	26	13	29	21
								Statistical significance ($P > F$)‡							
Manure		0.20	0.87	0.17	0.03	0.40	0.51	0.12	0.97	0.13	0.02	0.25	0.52	0.06	0.30
Fertilizer		0.10	0.03	0.08	0.01	0.01	0.02	0.01	0.01	0.96	0.36	0.01	0.01	0.01	0.06

†Fertilizer P treatments were reapplied for second-year crops, except at Sites 1, 11, and 12.

‡No manure by fertilizer interaction was observed at any site ($P \leq 0.05$).

Table 9 . Effect of manure applied before a first crop and fertilizer application on soil-test P extracted by Mehlich-3 for soil sampling after harvesting second-year crops at each site. Sites 5 and 10 were not evaluated on the second-year.

Manure	Fertilizer	Site													
Treat.	rate†	1	2	3	4	6	7	8	9	11	12	13	14	15	16
	kg P ha^{-1}	mg P kg^{-1}													
Control	0	16	43	33	21	61	18	16	16	34	48	14	14	22	22
	10	18	47	32	20	66	18	24	22	33	51	18	19	24	40
	20	19	64	43	24	76	21	28	29	26	48	30	21	28	58
	30	16	53	44	26	81	29	32	32	29	48	31	26	32	56
Low	0	15	37	42	22	50	21	22	18	25	55	21	17	30	43
	10	20	59	38	26	70	19	26	22	25	55	27	21	32	26
	20	21	45	43	35	80	21	31	23	32	52	39	21	33	42
	30	26	60	47	34	96	36	34	26	28	66	54	31	47	55
High	0	18	50	49	23	41	17	23	18	34	63	23	19	42	18
	10	20	60	51	29	37	22	32	23	33	57	33	18	36	31
	20	25	56	65	32	40	29	44	29	33	87	45	21	32	39
	30	24	69	54	27	49	35	44	31	36	73	53	25	52	39
		Statistical significance ($P > F$)‡													
Manure		0.05	0.67	0.27	0.03	0.48	0.48	0.11	0.88	0.42	0.01	0.20	0.43	0.03	0.43
Fertilizer		0.01	0.01	0.18	0.03	0.01	0.01	0.01	0.01	0.99	0.33	0.01	0.01	0.01	0.02

†Fertilizer P treatments were reapplied for second-year crops, except at Sites 1, 11, and 12.

‡No manure by fertilizer interaction was observed at any site ($P \leq 0.05$).

Table 10. Soil-test P before treatment application, after harvesting first-year and second-year crops, and total P removal in grain from two crops for manure treatments across sites. Sites 5 and 10 were not evaluated on the second-year.

Soil			Manure	Control				Low manure rate				High manure rate			
Class	Site	BPi†	rate	BP1‡	BP2§	TP rem¶	Change#	BP1	BP2	TP rem	Change	BP1	BP2	TP rem	Change
		mg P kg^{-1}	kg P ha^{-1}	mg P kg^{-1}		kg P ha^{-1}		mg P kg^{-1}		kg P ha^{-1}		mg P kg^{-1}		kg P ha^{-1}	
Low	1	14	23-47	15	13	41	-2	17	12	39	-2	19	15	43	1
	7	11	23-53	15	15	45	3	14	20	57	7	17	15	55	4
	13	11	26-51	12	12	32	0	20	18	35	7	21	19	38	9
	14	13	33-61	12	14	46	1	14	17	44	3	17	19	46	7
	Mean	12		12	14	41	1	15	17	44	3	18	17	46	4
Opt.	4	19	27-54	31	18	51	-2	33	20	50	0	38	21	53	4
	9	17	19-37	17	15	38	-7	34	18	46	3	27	18	42	2
	15	19	49-99	17	22	45	2	18	27	49	8	28	39	48	22
	Mean	18		22	18	45	-2	28	22	48	3	31	26	48	9
High	2	34	32-63	39	44	41	10	37	39	48	6	48	54	53	19
	3	25	44-74	32	24	44	-3	30	32	45	6	32	32	57	10
	6	49	36-68	46	51	35	42	43	44	47	35	30	33	43	24
	8	37	29-42	18	15	43	-25	24	20	45	-16	25	22	42	-13
	11	22	28-56	31	27	49	3	21	19	48	1	33	30	52	7
	12	52	36-71	54	42	43	-13	57	48	45	-5	77	55	47	8
	16	28	26-52	29	20	46	-18	39	36	52	12	24	17	54	-4
	Mean	42		43	32	43	-1	39	34	48	5	45	34	51	6

† Bpi, Bray-1 initial, before treatment application.
‡ BP1, Bray-1 after harvesting the first-year crop.
§ BP2, Bray-1 after harvesting the second-year crop.
¶ TP rem, P removed in grain by two crops.
# Change, BP2 minus BPi.

Table 11. Soil P relative to the control plots (no manure or fertilizer) after applying approximately similar rates of fertilizer or manure extracted by three routine tests (Bray-1, Olsen, and Mehlich-3) and two environmental tests (Fe-oxide and water extraction), for samples collected after harvest of the first-year crops.

	Bray-1		Olsen		Mehlich-3		Fe-oxide		Water		Statistics		
Site†	Fertilizer	Manure	Fertilizer	Manure	Fertilizer	Manure	Fertilizer	Manure	Fertilizer	Manure	Source	Test	S*T‡
	.... Relative extraction										.... (*P* > *F*)		
1	1.43	1.20	1.42	1.13	1.49	1.33	1.12	1.05	1.38	1.15	0.01	0.11	0.89
2	1.03	0.95	1.09	1.04	1.02	0.94	0.97	0.97	0.94	1.00	0.60	0.83	0.92
4	1.03	1.07	1.01	1.06	1.00	1.04	1.02	1.00	1.12	1.15	0.54	0.45	0.99
5	1.41	1.71	1.25	1.58	1.38	1.86	1.21	1.37	1.00	1.14	0.01	0.01	0.45
6	1.28	0.94	1.15	1.02	1.19	0.95	0.99	1.00	1.40	0.93	0.01	0.62	0.27
7	1.36	0.91	1.46	1.08	1.47	0.92	1.20	0.83	1.50	1.00	0.01	0.01	0.57
8	2.11	1.36	2.22	1.89	2.19	1.71	1.87	1.40	2.36	1.73	0.01	0.04	0.71
9	1.98	2.02	2.14	2.07	1.75	1.86	1.62	1.84	2.27	2.27	0.64	0.08	0.95
10	1.03	1.10	1.02	1.20	1.12	1.23	0.97	1.09	1.13	1.44	0.11	0.47	0.93
11	0.94	0.69	1.00	0.62	0.94	0.63	0.84	0.73	0.87	0.68	0.11	0.98	0.47
12	1.07	1.05	1.08	1.12	1.04	1.08	1.05	1.08	1.00	1.17	0.04	0.71	0.09
13	1.46	1.59	1.56	1.52	1.46	1.58	1.41	1.38	1.46	1.38	0.55	0.08	0.29
14	1.54	1.16	1.50	1.15	1.52	1.10	1.76	1.08	1.38	1.00	0.01	0.19	0.38
16	1.71	1.36	1.83	1.56	1.72	1.50	1.72	1.21	1.88	1.44	0.01	0.11	0.46
Mean	1.41	1.30	1.41	1.32	1.38	1.33	1.31	1.20	1.41	1.28	0.07	0.71	0.99

†Site 3 and 15 were not included.

‡ S*T, interaction between P source and soil P test.

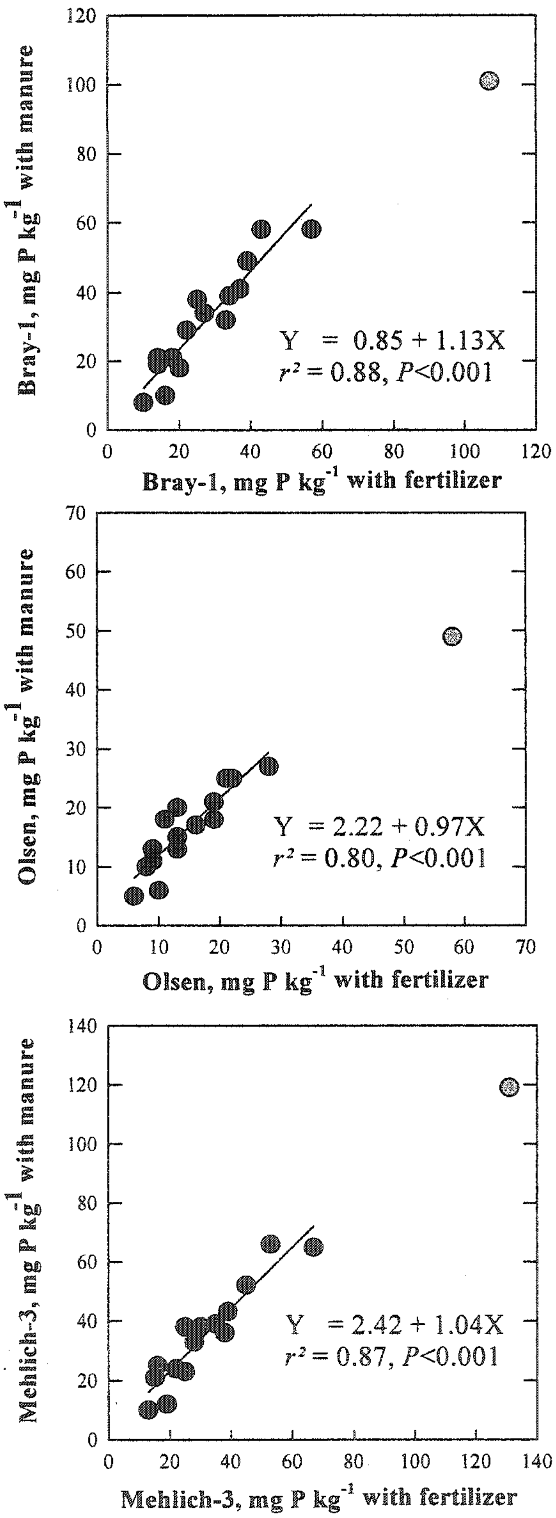

Fig. 1. Relationships between STP for fertilized and manured soils with similar P rates. The gray data point (Site 10) was not included for the regression.

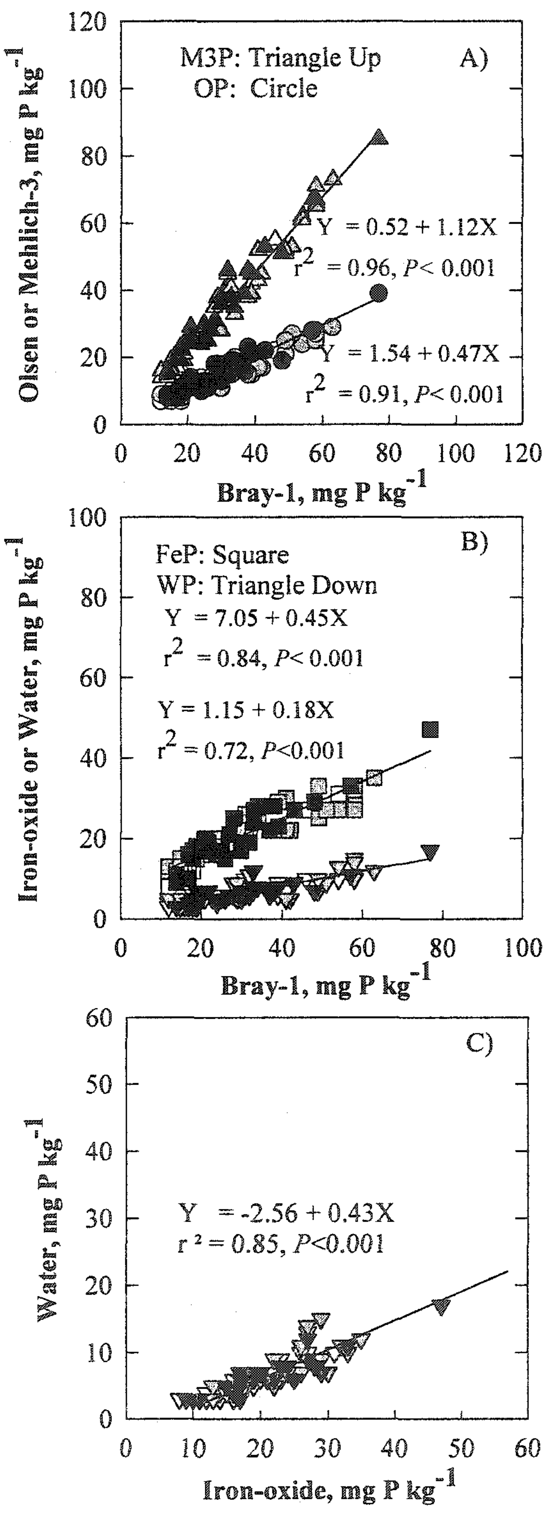

Fig. 2. Relationships between Bray-1 and a) Mehlich-3 or Olsen. Bray-1 and b) Iron-oxide or Water tests; and c) Iron-oxide and Water tests, for control (empty symbol), fertilizer (gray symbol), and manure (full symbol) plots.

CHAPTER 4. SOIL-PHOSPHORUS TEST RESPONSE TO FIXED- AND VARIABLE-RATE LIQUID SWINE MANURE APPLICATION FOR SOYBEAN-CORN ROTATIONS

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ABSTRACT

Variable-rate (VR) technology can be used to vary nutrient application rates within a field. This technology allows for a more efficient nutrient application and potentially can increase crop yield while reducing excess nutrient application to some field areas. Excess nutrient application and loss from fields can reduce water quality. The objective of this study was to compare VR and uniform or fixed rate (FR) application of liquid swine manure on soil-test P (STP) spatial variability in two Iowa fields. Treatments were a control (no manure), FR based on field-average STP, and VR based on STP from 0.1 to 0.3 ha grid-sampling cells. Manure was applied with commercial VR spreaders equipped with differential global positioning systems (DGPS). Iowa P recommendations for the 2-year crop rotation were used. Soil-test P was measured by the Bray-1 P test. Conventional statistics (standard deviation) and a Markov random field approach were used to assess changes in variability of STP due to treatment application. There was high initial within-field variability in both fields, which encompassed the five Iowa STP interpretation categories for crops. The VR manure application method reduced STP variability in both fields, probably because more P was applied to low-testing field areas and less or no P was applied to high-testing areas. Markov random field was a useful tool for studying spatial distributions of STP, although in this study the conclusions were similar for the two methods used to study variability. Additional work to adapt Markov random field

models to experimental procedures used in this study could result in more robust assessments of differences between treatments.

INTRODUCTION

Soil-test P (STP) variability is caused by natural factors such as climate, soil parent material, biological activity, and topography, and by human management practices (Sauer and Meek, 2003). Many authors have reported very high STP spatial variability in agricultural fields (Mallarino, 1996; Borges and Mallarino, 1998; Schepers et al., 2000; Sauer at Meek, 2003). Variability in STP leads to differences in fertilizer needs and grain yield within a field (Sawyer, 1994; Wollenhaupt et al., 1994; Mallarino, 1996). Fertilizer or manure rates are frequently determined based on the average soil nutrient level of a few soil samples collected across a field, and one single rate often is applied to the whole field. This practice leads to over-application of nutrients in field areas where nutrients are already adequate and under-application in areas where the nutrients are deficient. Variable-rate application is a recent technology that was developed as consequence of recognizing the spatial variation of crop nutrient needs within fields (Sawyer, 1994). It can be used to increase the efficiency of fertilizers or manure use and to reduce the risk of water quality impairment due to excess nutrient application and loss from fields (Wittry and Mallarino, 2002; Eghball et al., 2003; Wittry and Mallarino, 2002). Other emerging technologies such as yield monitors, global positioning systems (GPS), and remote sensing facilitate quantifying and examining the effects of nutrient spatial variability on crop production and farm profitability (Schepers et al., 2000). Field studies comparing effects of VR and FR for fertilizer or manure P application have not demonstrated yield increased due to VR use (Anderson and Bullock, 1998; Lowenberg-DeBoer and Aghib, 1999; Wittry and Mallarino, 2002 and 2004). However, studies have shown VR can reduce both amounts of nutrient applied and soil nutrient variability (Anderson and Bullock, 1998; Lowenberg-DeBoer and Aghib, 1999; Weisz and Heiniger, 2003; Wittry and Mallarino, 2004).

Traditionally, field experiments have been conducted in small plots and the most common design used has been the randomized complete-block design. Recently, on-farm research based on replicated strips has become an accepted methodology that complements the traditional small-plot research. Treatments are applied to narrow (usually related to the width of the combine) and long strips (usually the length of the field). Randomized block design continues to be the most popular design for field experiments because it is easy to implement and analyze, and it is based on the concepts of randomization, blocking, and replication (Cressie, 1993; Bhatti et al., 1991) to account for spatial variability. Randomization is assumed to neutralize spatial correlation of measurements, replication allows for hypothesis testing, and blocking is expected to reduce residual variation and improve tests of treatments effects. However, spatial positions of the treatments are ignored (Cressie, 1993) and spatial correlation of measurements may not be accounted for appropriately. Classical statistical methods such as analysis of variance (ANOVA), analysis of covariance, and regression analysis are commonly used to interpret results and evaluate treatment effects and conclusions are then extrapolated to large areas. Overlooking the strong spatial autocorrelation of soil properties could lead to weak conclusions (Bhatti et al., 1991; van Es and van Es, 1993).

Statistical and mathematical procedures that account for spatial correlations such as variograms, kriging, spectral, nearest neighbor analysis, and fractal analyses attempt to characterize better the complex relationships between many soil properties and (or) crop response in agriculture fields (Bhatti et al., 1991; Stroup et al., 1994; Cambardella et al., 1994; Mallarino, 1996; Kravchenko and Bullock, 1999; Kravchenko et al., 2000). Extensive efforts have been dedicated for a long time to develop improved statistic methods that account for spatial correlation in experimental designs for agriculture trials. Spatial considerations were addressed as early as in the 1930's (Cressie, 1993). Only recently, however, studies have focused on adapting some of these techniques to on-farm strip trials (Bhatti et al., 1991; Stroup et al., 1994, Mallarino et al., 1998; Bermudez and Mallarino, 2002; Ferguson et al., 2002; Eghball et al., 2003). Some of these studies have compared VR and FR application of nutrients using classical statistical analyses or the new techniques that include spatial considerations, such as studies of Mallarino et al. (1998), Ferguson et al. (2002), and Ehgball et al. (2003).

An alternative approach to the quantification and description of spatial dependence is by using Markov random field models. Markov random field models have been applied to characterize the spatial dependence of particulate matter air pollution in Pennsylvania (Kaiser et al., 2002) and spatio-temporal rainfall amounts (Allcroft and Glasbey, 2003). This model has received very little attention for agriculture field experiments (Besag and Higdon, 1999). Therefore, the objective of this research was to (1) compare STP spatial variability after using VR and FR liquid swine manure application methods and (2) adapt Markov random field models to examine the spatial dependence of STP after applying these treatments.

MATERIALS AND METHODS

Field methods

The STP data used in this study come from two field strip-trials located in Buchanan county, Iowa, that were managed with a soybean-corn rotation. A rectangular area of approximately 15 ha of each field was selected for the experiments. Table 1 shows relevant information about soil types and selected chemical properties for both fields. Initial composite soil-samples (12 cores, 15-cm depth) were collected using a grid-point sampling method (Wollenhaupt et al., 1994). Grid lines were spaced approximated 55 m in both directions (large cells) and cores were collected from approximately 100-m^2 near the center of each cell. Coordinates of the center of soil sampling areas were recorded using a GPS device with differential correction. Soil samples were analyzed for P by the Bray-1 test (Frank et al., 1998). Treatments applied were a control with no manure application, a FR of manure applied before soybean based on the P removal in grain by the two fields, and a VR of manure based on the value of STP for each sampling cell, following Iowa STP interpretation classes and fertilizer recommendations (Sawyer et al., 2002). Interpretation classes <8 mg kg^{-1} for Very Low, 9 to 15 mg kg^{-1} for Low, 16 to 20 mg kg^{-1} for Optimum, 21 to 30 mg kg^{-1} for High, and >31 mg kg^{-1} for Very High. The VR of manure were targeted to supply 85 kg P ha^{-1} for areas testing Very Low, 68 kg P ha^{-1} for areas testing Low, 42 kg P ha^{-1} for areas testing Optimum, and no manure for areas testing High and Very High. The FR of manure was calculated to apply 50 kg P ha^{-1}, which is the average expected P removal for the two crops of the rotation.

Treatments were applied before planting crops to strips 18.3-m wide and 605-640 m long. Randomized complete-block designs were used in both fields. There were five blocks (replications) in Field 1 and four in Field 2. Liquid swine manure from the same underground storage pit was used for both fields. No commercial P-fertilizer was applied while the experiment was conducted. The manure was broadcast using a slurry tank spreader equipped with a differential GPS receiver, a flow meter, and a controller. The manure was incorporated by chisel plowing or disking. Georeferenced manure application maps were prepared and uploaded into the equipment computer and the manure was incorporated by chisel-plowing and disking.

Methods for grain yield harvest and results were published before (Wittry and Mallarino, 2002) and are not presented or discussed in this paper. After crop harvest, composite soil-samples (12 cores from a 15-cm depth) were collected for STP analysis from 100-m^2 areas near the center of small cells (55 by 18.3 m) defined by the initial soil sampling grid lines along crop rows and the width of each treatment strip across crop rows. The center of all the small cells was registered using a GPS device. The same locations were sampled each of four years. There were 60 locations for each treatment in Field 1 (12 locations per strip), and 44 locations for each treatment in Field 2 (11 locations per strips). Figure 1 shows the experiment design and point sampling grids.

Data analyses

Soil-test P maps were generated using the geostatistic tool of ArcGIS 8.3 (Environmental Systems Research Institute, 2001), and appropriate files were exported for statistical analyses. Conventional descriptive statistics for STP data were calculated by using the UNIVARIATE procedure of SAS (SAS Institute, 2000). To develop separate STP maps for each treatment, data for each treatment were extracted from the complete dataset, then kriged as if the whole field area had received that particular treatment. Kriging is an exact interpolator because it uses the best local average that coincides with the values of the data points.

Geostatistics were used to analyze spatial variability of STP before and after treatment application. Spatial analysis after treatment application for each treatment across fields was done assuming that only strips for each treatment were present each time. Spatial structure [$\gamma(h)$] was characterized by sample variograms using the following equation:

$$\gamma = \frac{1}{2}\sum_{i=1}^{n} [Z(s_i + h) - Z(s_i)]^2$$

Where s_i and $s_i + h$ are sampling locations separated by a distance h, $Z(s_i)$ and $Z(s_i + h)$ are measured values of the variable Z at the corresponding locations, and n is the total number of sample pairs for the distance h. The nugget of the variogram represents the random variation in the data spatial variability. The range represents the distance beyond which data become independent or are no longer correlated with each other. The maximum variability value is called the sill. The ratio of the nugget to the sill characterizes the importance of the random component in the whole field spatial variability of the data. This ratio has been proposed as an index to measure the spatial dependence in soil properties (Cambardella et al., 1994; Kravchenko et al., 2000). If this ratio is between 0.25 and 0.75 the variable has moderate dependence. A low value indicates strong dependence, and a high value indicates weak dependence. A spherical model fitted best to sample semivariance values (using weighted least squares regression) compared with linear and gaussian models and is the only one presented.

Markov random field model formulation

The model developed in this study for analysis of STP data was formulated using a Markov random field model approach. The assumption of the model is that given values at all the other locations, the distribution of $Z(s_i)$ depends only on those values at locations within its neighborhood. An idealized model for all the locations and neighborhoods for analysis within time for the particular design of our experiments could look as in the following notation.

Let $s_i \equiv (u_i, v_i)$ denote the spatial location, where u_i denotes the horizontal coordinate, and v_i the vertical coordinate for all $i = 1,\ldots n$. The general notation for the four nearest neighbors is as follows:

$$\text{Let } N_i \equiv \{s_j{:}(u_j = u_i, v_j = vi \pm 1), (u_j = u_i \pm 1, v_j = v_i)\}$$

In our model, the three treatments (control, fixed, and variable) and soil sampling design produce six different types of neighbors, denoted as:

$$N_i^{cc} \equiv \{sj{:}sj \in Ni \text{ and } s_i, s_j \text{ are c,c pair}\}$$

$$N_i^{ff} \equiv \{sj{:}sj \in Ni \text{ and } s_i, s_j \text{ are f,f pair}\}$$

$$N_i^{vv} \equiv \{sj{:}sj \in Ni \text{ and } s_i, s_j \text{ are v,v pair}\}$$

$$N_i^{cf} \equiv \{sj{:}sj \in Ni \text{ and } s_i, s_j \text{ are c,f pair}\}$$

$$N_i^{cv} \equiv \{sj{:}sj \in Ni \text{ and } s_i, s_j \text{ are c,v pair}\}$$

$$N_i^{fv} \equiv \{sj{:}sj \in Ni \text{ and } s_i, s_j \text{ are f,v pair}\}$$

$$N_i = N_i^{cc} \cup N_i^{ff} \cup N_i^{vv} \cup N_i^{cf} \cup N_i^{cv} \cup N_i^{fv}$$

Our random variable will be denoted as $Z(s_i)$ = P (soil-test P) or logP (log of soil-test P) at s_i.

$$Z(N_i) = \{Z(si){:}sj \in Ni\}$$

The full conditional density of the random variable is given by:

$f_i\,(Z(s_i)|\ \{Z(s_j) : j \neq i\ \}) = f_i\,(Z(s_i)\ |\ Z(N_i))$

We assume that these densities are normal with means μ_i and variances τ_i^2 for i=1,...n. The conditional means μ_i for the entire model within time would be:

$$\mu_i = \alpha_i + \eta_{cc}\sum_{N_i^{cc}}\{Z(s_j - \alpha_j)\} + \eta_{ff}\sum_{N_i^{ff}}\{Z(s_j - \alpha_j)\} + \eta_{vv}\sum_{N_i^{vv}}\{Z(s_j - \alpha_j)\} +$$

$$+\ \eta_{cf}\sum_{N_i^{cf}}\{Z(s_j - \alpha_j)\} + \eta_{cv}\sum_{N_i^{cv}}\{Z(s_j - \alpha_j)\} + \eta_{fv}\sum_{N_i^{fv}}\{Z(s_j - \alpha_j)\}$$

where $\alpha_i = \mu_c$ if s_i is control, μ_f if s_i is fixed, μ_v if s_i is variable. The conditional variances τ_i^2 would be:

$\tau_i^2 = \tau_c^2$ if s_i is control, τ_f^2 if s_i is fixed, τ_v^2 if s_i is variable. The global joint distribution is considered to be Gaussian, with a mean of α, and a variance matrix, as this notation:

$Z \sim \text{Gau}\ (\alpha, (I\text{-}C)^{-1} M)$

Where I is the N x N identity matrix, M is an N x N = diagonal matrix, and C is an N x N matrix.

The spatial STP variation was assessed using Markov random field for sampling points along each strip. Field 1 had 12 points in each strip, and Field 2 had 11 points. There were five strips for each treatment in Field 1 and four strips in Field 2. The model described was fitted to STP for the sampling date of the initial year and the following four years in both fields.

A logarithmic transformation for the variable STP in all sampling dates was used to ensure non-negativity. A Gaussian conditional model for each strip was formulated to specify full conditional probability density function:

$$f_i(Z(s_i)|\ \{Z(s_j):\ j \neq i\}) = \frac{1}{\sqrt{2\pi\tau_i^2)}}\exp[-\frac{1}{2}\tau_i^2(z(s_i - \mu N_i)^2]$$

Where the conditional mean for site i is:

$$\mu_{N_i} = \alpha + \eta\sum_{j \in N_i}(z_j - \alpha)$$

and $Z(s_i)$, $Z(s_j)$= logP measured at location s_i and s_j

Our approach to estimation was maximum likelihood. The parameters estimated were η, and τ^2, and were estimated using centered data of logarithmic $Z(s_i)$, by subtracting the mean to the transformed data. Conditional expected values were generated using those parameters. Mean squared predictor errors (MSPE) using the conditional expected values were computed to assess and compare the estimator parameter of spatial dependence η among strips. In this conditionally specified model, the small-scale structure is entirely captured in the dependence matrix and isotropy is assumed.

RESULTS AND DISCUSSION

There was high variability of STP values for the two fields and for all soil sampling dates (Table 2). Soil-test P encompassed at least four ISU interpretation classes in both fields. Analysis of variance of treatment effects on STP showed that manure application effects were statistically significant ($P < 0.05$), except for one sampling date at Field 2 (Table 3). However, the manure application methods did not differ at any site or sampling date. Because there was a differential application of manure P with the VR method (higher in low-testing areas and small or no amount of manure in high-testing areas), this result implies that any average, net STP change across the experimental areas due to VR was not large enough to differ from values resulting from using the FR method. Results for total manure P applied for this study (Wittry and Mallarino, 2002) indicated that 11% more manure was applied with FR than with VR. However, analyses of treatment effects for field areas that tested within different Iowa STP interpretation classes (Barbazán et al., 2003; Wittry and Mallarino, 2004) showed that application methods often differed and changed the distribution of STP. The VR method increased STP more than the FR method in field areas initially testing very low or low according to Iowa STP interpretations, the methods often did not differ for areas testing optimum, and FR increased STP more than VR high or very high field areas. These results are reasonable because that was the intended affect for VR and also demonstrate that use of this technology achieved its objective. Furthermore, Barbazán et al. (2003) showed that similar results were observed for three routine soil P tests (Bray-1, Mehlich-3, and Olsen) and two environmental soil P tests (P extracted with water and with the Fe-oxide impregnated filter paper test.

An analysis of SD observed for VR and FR application methods (Table 2) shows that in both sites STP variability for VR was only slightly smaller than for FR in the first sampling date after the first manure application. However, SD for VR was clearly smaller than for FR for sampling dates after the second manure application. This result was expected because repeated used of VR should result in increasing STP uniformity across a field. A smaller variability for the VR method was confirmed by tests for equality of variances using the TTEST procedure of SAS (SAS Institute, 2000). Such tests showed significantly smaller ($P < 0.05$) variance of STP for VR compared with FR in 2000 for Field 1 and 2001 for Field 2 (Table 4), while the methods also differ in 2000 for Field 2 but only in 2000 for Field 1 ($P < 0.05$). Homogeneity of variance across treatments is a basic assumption of ANOVA, which obviously was not the case for those sampling dates. This result suggests cautious conclusions from hypothesis testing of results for these sampling dates that were addressed above.

Omnidirectional semivariograms constructed with initial soil sampling before treatment application confirmed the strong or moderate spatial dependence structure for soil-test P in both fields (Fig. 2). The ranges were 240 m for Field 1 and 200 m for Field 2. The ratio of the nugget to the sill was 0.43 for Field 1 and 0.36 for Field 2. Sample semivariograms showed that the structure of the spatial variability of STP differed among fields (Table 4). Parameters such as the sill (which is an estimate of total variability) and nugget (the random variability) indicated that the spatial structure of STP was more variable for Field 2 than for Field 1. After treatment application within fields, parameters of semivariograms showed that in Field 2, VR decreased nugget and sill parameters compared with FR, but in Field 1 only the sill decreased. The decrease in the total variability for VR was greater in the last soil sampling date for both fields. The results from these sample variograms agree with the SD results. In Field 1 the nugget parameter slightly increased with VR. We expected that manure applied with VR would reduce both random and spatially structured variability by increasing the STP at low-testing areas and decreasing or not affecting the high testing areas. The results found with SD also indicated that the VR application method usually reduced yield variability compared with the FR method.

Patterns of STP in both fields for the three treatments are shown in Fig. 3 and 4. When analyzing the patterns, the assumption for each VR and FR treatments was that the corresponding strips for each treatment were an entire field and data for the other treatment were omitted. The distribution pattern of STP for VR (Field 1, fall 2000) indicated large and more homogenous areas for values in the optimum interpretation category (16 - 20 mg P kg^{-1}) while FR had a more heterogeneous distribution of values that ranged from the low to very high interpretation classes (9 to >31 mg kg^{-1}). For example, in fall 2001 the very high STP values for FR were concentrated in the northeast corner of Field 2. Visual observation of the map patterns indicate that VR tended to reduce the STP extremes values at the sampling date of fall 2000 for both fields compared with FR. Studies comparing VR and FR for N have yielded different results. Eghball et al. (2003) using multifractal analysis found that VR for N did not reduce variability of soil NO_3-N compared with FR. Also, Ferguson et al. (2002) concluded that VR for N did not decrease spatial variability when compared to FR. These results for N could be expected because of high temporal variability associated with its mobility in soils.

Results of Markov random field model calculations are shown in Tables 5 and 6, which show parameter estimates of the models for each treatment strip and year. Strips for the control treatment (no manure applied) had MSPE consistently smaller than those for VR and FR treatments. Similar values for mean squared predictor errors (MSPE) are useful to compare the η values for VR and FR manure application methods. Smaller values of the η parameter indicate less spatial dependence than higher values. The η values for FR were higher than VR in eight strips of a total of 20 in Field 1 and in five of a total of 16 in Field 2. The parameter η was in average across all strips higher for FR than for VR for both fields for each soil sampling date. These differences between treatments became more pronounced with years following initiation of the treatments. Previous P and cropping management practices may have influenced the differences between treatment variability in some areas of the fields than others. However, no direction of the variability was included in the analysis of this data.

CONCLUSIONS

Variable-rate liquid swine manure application resulted in less STP variability across two fields than a fixed-rate application method. Consistent patterns of spatial variability of STP were observed across years. Application of Markov random field models to study of STP variability was useful to describe and summarize variability differences among the treatments applied in this study. However, the general conclusions from their use were similar to study using classical or geostatistical analyses. More studies are needed for other spatial structures and to include a parameter for directionality.

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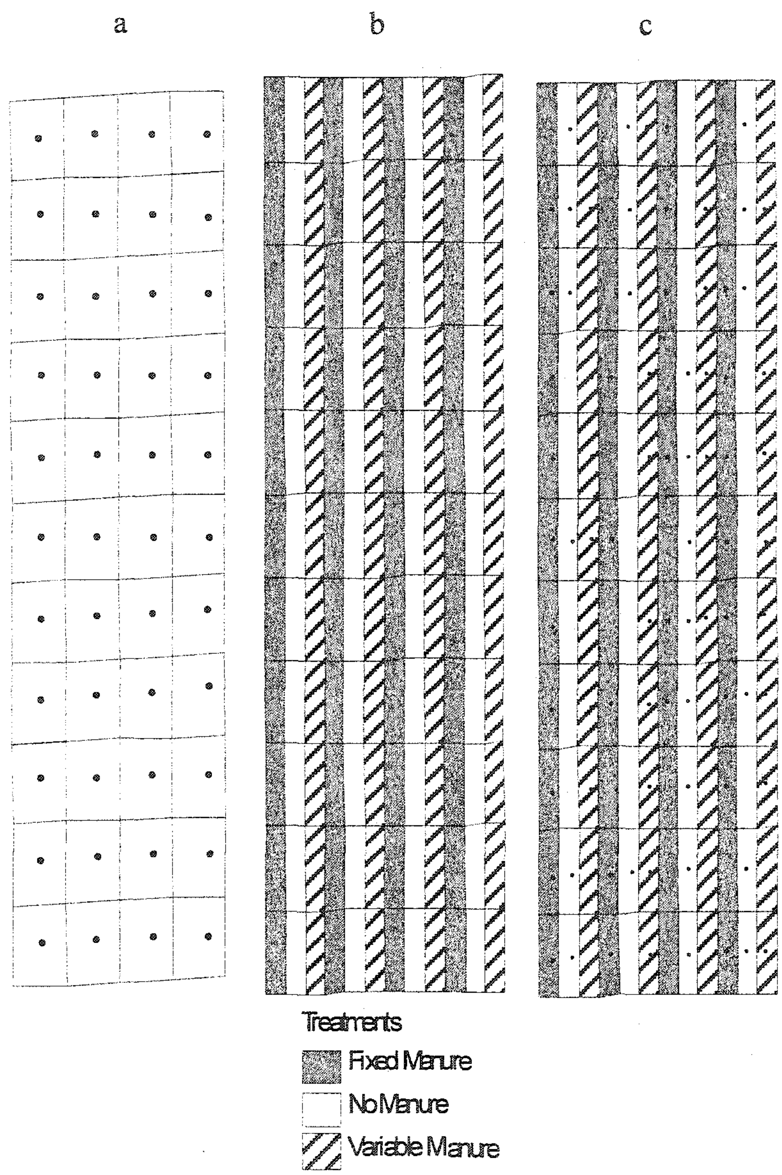

Figure 1. Experimental design used in Field 2, showing a) initial grid sampling points, b) treatments and replications, and c) soil grid sampling points after harvesting the first crop.

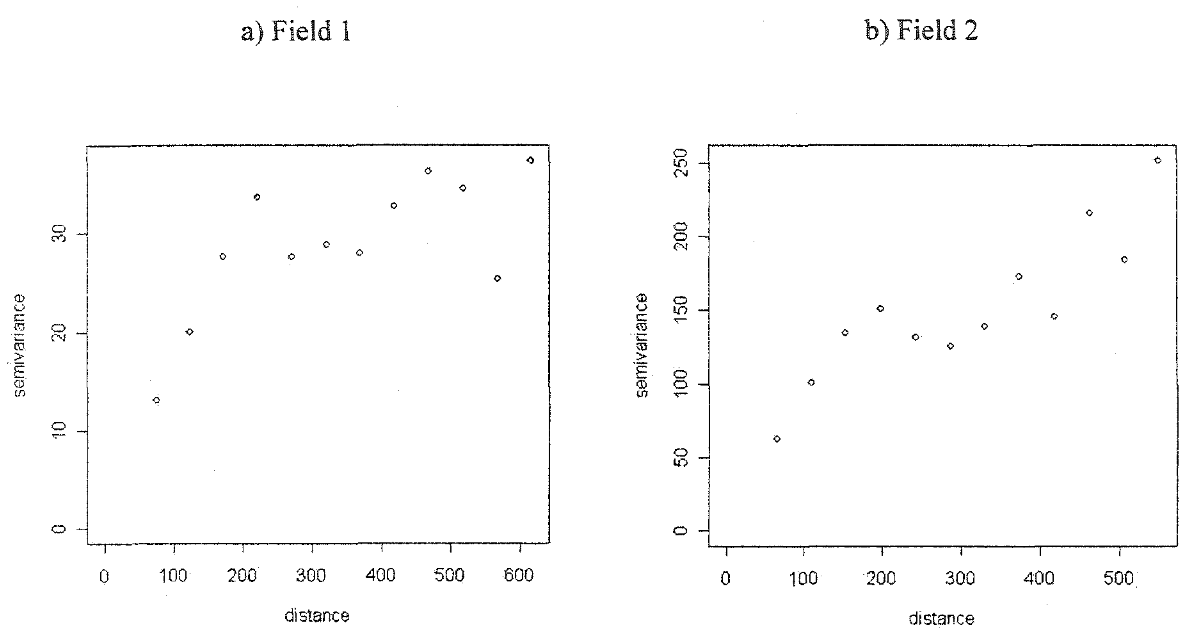

Figure 2. Sample semivariograms for the initial soil sampling (distance in meters).

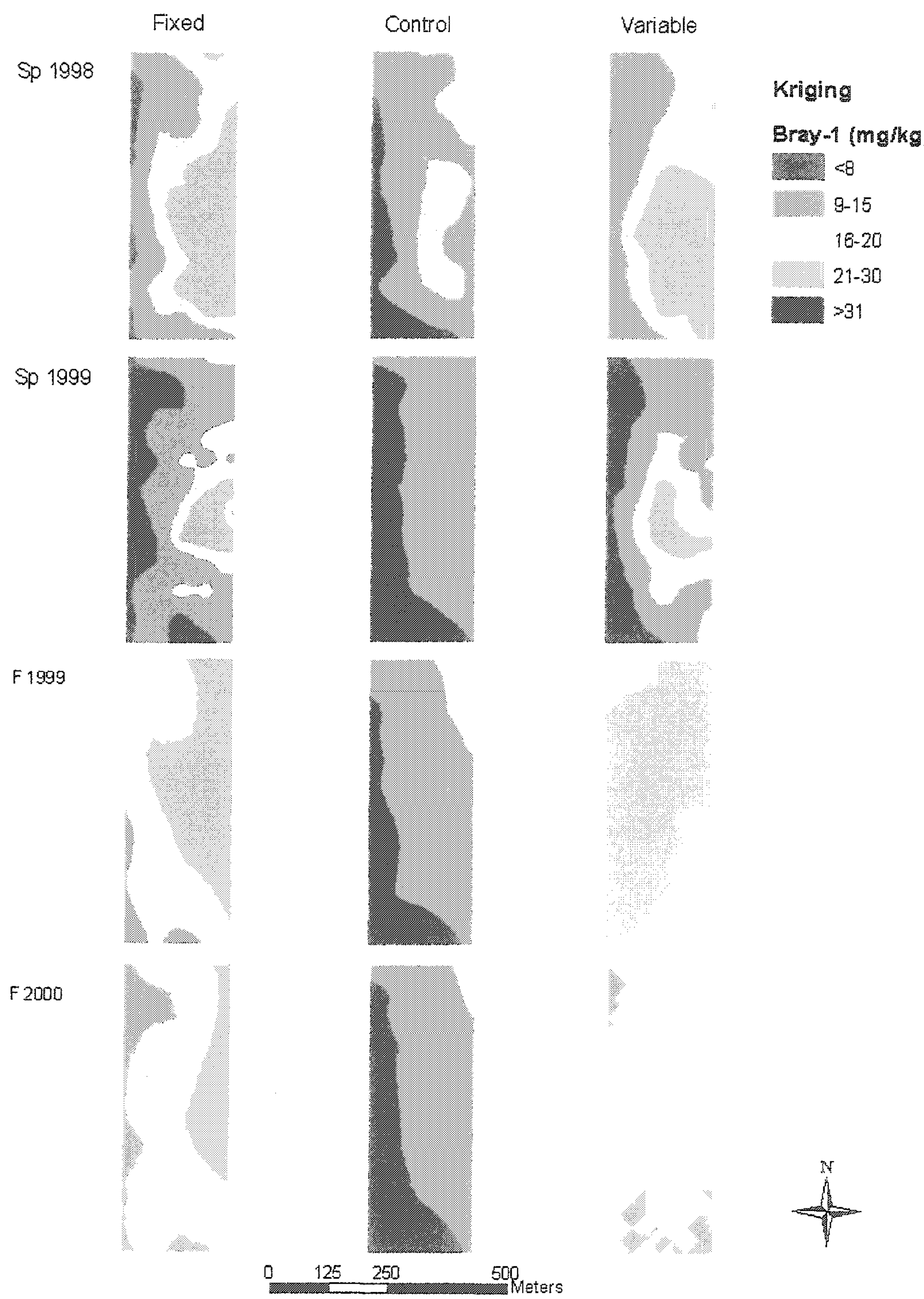

Figure 3. Kriged maps of soil-test P for Field 1, 1998 through 2000.

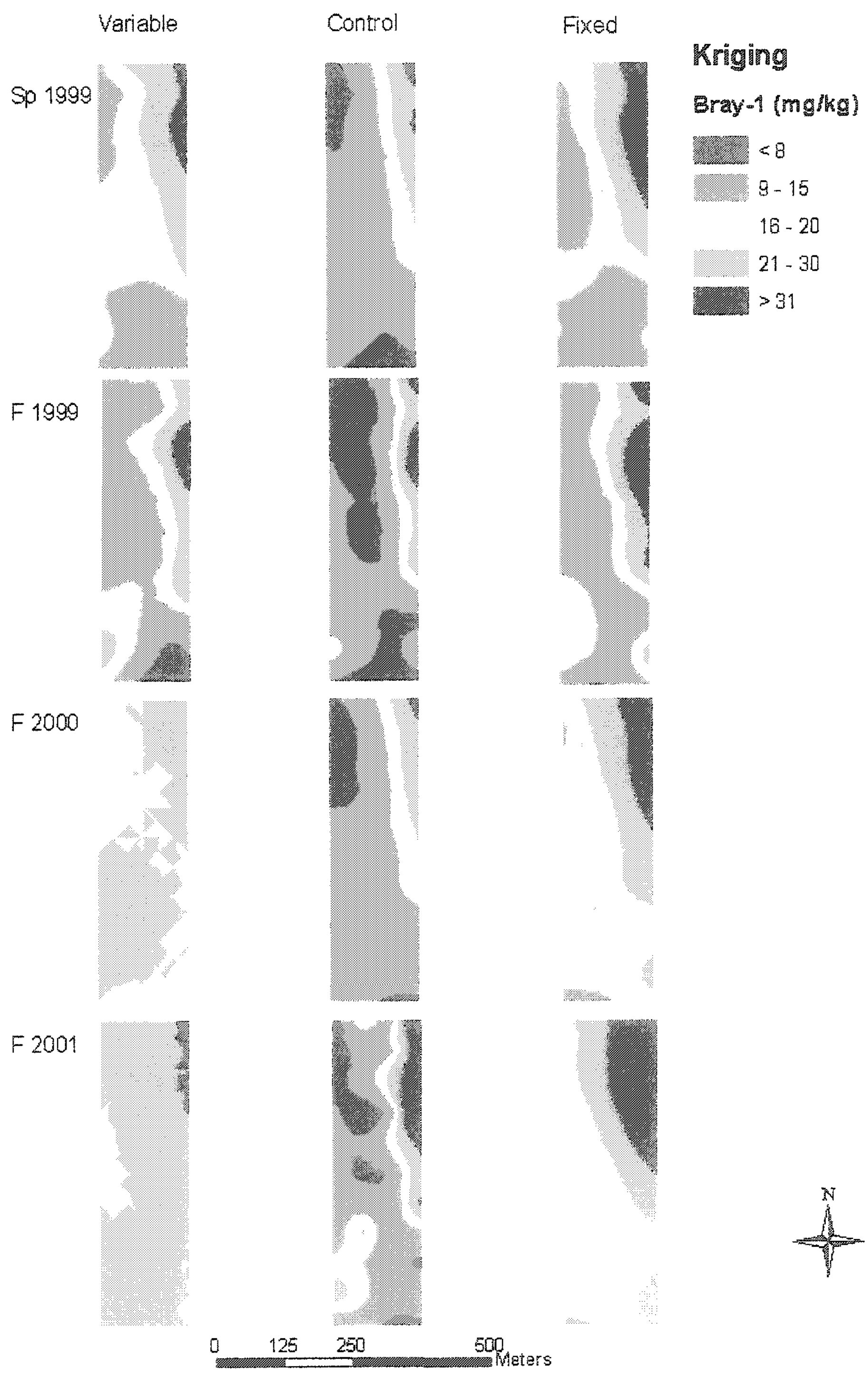

Figure 4. Kriged maps of soil-test P for Field 2, 1999 through 2001.

Table 1. Information about selected soil properties for Field 1 and Field 2.

	Predominant soil				Second dominant soil			
Field	Classification†	Area	OM‡	pH	Classification	Area	OM	pH
		%	g kg^{-1}			%	g kg^{-1}	
1	Clyde (T. Endoaquoll)	46	38	6.7	Kenyon (T. Hapludoll)	13	43	6.7
	Floyd (A. Hapludoll)							
2	Clyde (T. Endoaquoll)	45	54	7.0	Readlyn (A.Hapudoll	29	36	7.0

† A.= Aquic; T. = Typic

‡ Soil organic matter

Table 2. Descriptive statistics for soil test P (Bray-1) by treatment and sampling date in two strip trials.

Field	Sampling date	Treat.	Statistics				
			Min	Max	Mean	Median	SD
			------------ mg kg^{-1} ------------				
1	Spr.1997	None	4	22	12	13	5.2
	Spr.1998	C	4	22	13	13	4.9
		VR	7	36	18	17	7.5
		FR	5	34	17	17	7.6
	Spr.1999	C	3	17	10	10	3.8
		VR	4	25	13	12	5.8
		FR	4	31	13	12	5.7
	Fall 1999	C	3	24	11	11	4.5
		VR	11	37	22	21	6.3
		FR	7	38	21	20	7.0
	Fall 2000	C	4	19	10	9	4.1
		VR	8	27	17	16	4.4
		FR	8	33	18	18	5.8
2	Spr.1998	None	4	56	11	11	11.4
	Spr.1999	C	5	59	14	12	11.1
		VR	5	58	19	16	12.1
		FR	6	68	20	16	13.2
	Fall 1999	C	4	48	14	11	10.6
		VR	4	53	18	15	10.6
		FR	6	63	20	16	14.0
	Fall 2000	C	4	57	14	12	9.8
		VR	9	38	21	20	6.2
		FR	9	80	23	20	13.8
	Fall 2001	C	5	64	18	14	13.3
		VR	11	51	25	21	10.9
		FR	9	93	25	20	17.1

† Min, minimum; Max, maximum; SD, standard deviation.

Table 3. Effect of manure application on soil-test P as evaluated by classical statistical methods.

Field	Sampling date	Bray-1 Control	FR	VR	Statistics Treat	C vs. M†	FR vs. VR‡
		------------- mg kg^{-1}	-----------		---------------- $P > F$	------------------	
1	Spr.1998	13	17	18	0.01	0.01	0.45
	Spr. 1999	10	13	13	0.01	0.01	0.43
	Fall 1999	11	21	22	0.01	0.01	0.13
	Fall 2000	10	18	17	0.01	0.01	0.14
2	Spr. 1999	14	20	19	0.02	0.01	0.67
	Fall 1999	14	19	18	0.02	0.01	0.35
	Fall 2000	14	23	21	0.01	0.01	0.36
	Fall 2001	18	25	25	0.01	0.01	0.80

†Contrast C vs M = Control vs. manured = Fixed rate and variable rate

‡Contrast FR vs. VR = Fixed rate vs. V = Variable rate

Table 4. Effect of fixed-rate and variable-rate on STP variability and spatial structure.

Field	Sampling date	Treatment	Classical Statistics		Semivariogram parameters (spherical model)	
			SD	$P > F$	Nugget	Sill
1	Spr. 1998	Fixed	7.6	0.94	9	59
		Variable	7.5		18	47
	Spr. 1999	Fixed	5.7	0.89	0	41
		Variable	5.8		5	37
	Fall 1999	Fixed	7.0	0.41	27	28
		Variable	6.3		33	9
	Fall 2000	Fixed	5.8	0.04	20	17
		Variable	4.4		17	4
2	Spr. 1999	Fixed	13.2	0.55	66	189
		Variable	12.1		70	132
	Fall 1999	Fixed	14.0	0.07	61	155
		Variable	10.6		32	89
	Fall 2000	Fixed	13.8	0.01	80	188
		Variable	6.2		34	9
	Fall 2001	Fixed	17.1	0.01	108	321
		Variable	10.9		85	61

Table 5. Estimated parameter values and mean squared predictor errors of Markov random models for soil-test P for each strip and sampling date in Field 1.

	Block 1			Block 2			Block 3			Block 4			Block 5		
Parameter	V†	C†	F†	V	C	F	V	C	F	V	C	F	V	C	F
Spr. 1997															
η‡		0.173			-0.002			0.062			-0.307			-0.081	
τ^2 §		0.016			0.150			0.077			0.066			0.050	
MSPE¶		7.7			7.6			6.8			4.8			3.0	
Spr. 1998															
η	0.262	0.071	-0.160	-0.078	0.025	0.083	0.331	0.335	0.304	0.437	-0.137	-0.059	0.224	0.305	-0.001
τ^2	0.067	0.054	0.049	0.039	0.182	0.144	0.071	0.057	0.088	0.052	0.086	0.066	0.069	0.089	0.067
MSPE	10.1	7.4	9.5	8.9	7.3	9.6	9.3	7.2	8.0	6.4	5.5	7.8	5.5	3.9	4.0
Spr. 1999															
η	0.056	0.086	-0.209	0.099	0.176	0.317	0.341	0.273	0.057	0.427	-0.404	-0.164	-0.292	-0.037	0.274
τ^2	0.062	0.042	0.044	0.072	0.121	0.124	0.094	0.097	0.133	0.057	0.042	0.076	0.052	0.096	0.049
MSPE	7.7	6.0	7.8	7.3	6.0	7.5	7.9	5.6	6.2	4.7	4.2	5.3	3.7	2.6	3.5
Fall 1999															
η	0.19	0.459	-0.194	-0.164	0.220	0.276	0.197	0.387	0.394	-0.033	-0.013	-0.145	-0.313	0.265	0.190
τ^2	0.088	0.048	0.032	0.054	0.205	0.085	0.055	0.056	0.041	0.103	0.048	0.067	0.075	0.113	0.088
MSPE	9.5	7.1	10.8	9.0	6.4	9.3	9.1	6.0	7.9	10.4	5.2	9.8	8.9	3.6	6.5
Fall 2000															
η	-0.095	0.441	-0.226	0.192	0.226	0.037	-0.032	0.288	0.397	-0.024	-0.111	0.366	0.396	0.279	-0.159
τ^2	0.037	0.052	0.036	0.083	0.150	0.069	0.058	0.082	0.034	0.083	0.054	0.029	0.023	0.052	0.043
MSPE	8.2	6.5	10.0	8.4	6.0	8.7	8.1	5.6	7.1	8.4	4.5	9.2	6.8	3.3	6.3

† V, Variable; C, Control; F, Fixed.
‡ η, parameter of spatial dependence.
§ τ^2, conditional variance.
¶MSPE = Mean square predictor error.

Table 6. Estimated parameter values and mean squared predictor errors of Markov random models for soil-test P for each strip and sampling date in Field 2.

		Block 1			Block 2			Block 3			Block 4		
Sampling date	Parameter	F †	C †	V †	F	C	V	F	C	V	F	C	V
Spr. 1998	η		0.433			0.441			0.102			0.405	
	τ^2		0.291			0.068			0.169			0.101	
	MSPE		9.8			5.7			5.1			5.5	
Spr. 1999	η	0.226	0.316	0.395	0.442	0.02	0.102	-0.121	-0.226	-0.356	-0.429	0.391	0.328
	τ^2	0.374	0.381	0.274	0.136	0.128	0.204	0.106	0.096	0.136	0.076	0.119	0.141
	MSPE	11.4	9.7	10.7	7.5	5.6	6.6	7.1	4.8	7.6	7.1	5.2	7.0
Fall 1999	η	-0.06	-0.029	0.38	0.488	0.425	0.152	-0.139	-0.104	-0.35	-0.029	0.338	0.453
	τ^2	0.423	0.167	0.281	0.077	0.051	0.187	0.14	0.191	0.093	0.167	0.173	0.081
	MSPE	11.8	9.9	10.1	6.5	4.9	5.9	6.7	4.4	7.3	7.1	5.3	7.0
Fall 2000	η	0.202	0.409	0.318	0.266	-0.297	-0.336	-0.029	-0.028	-0.293	-0.125	0.48	0.388
	τ^2	0.306	0.206	0.072	0.058	0.063	0.028	0.102	0.12	0.062	0.086	0.083	0.05
	MSPE	12.4	9.5	9.3	8.4	5.9	8.8	8.4	5.2	10.0	7.8	4.7	8.2
Fall 2001	η	0.148	0.471	0.28	0.472	0.134	-0.061	0.187	0.202	-0.184	-0.344	0.41	0.344
	τ^2	0.376	0.208	0.17	0.056	0.097	0.074	0.128	0.156	0.163	0.066	0.132	0.099
	MSPE	12.8	10.6	10.7	9.4	6.4	9.3	9.0	6.6	10.7	7.7	5.4	9.0

† V, Variable; C, Control; F, Fixed.

‡ η, parameter of spatial dependence.

§ τ^2, conditional variance.

¶MSPE = Mean square predictor error.

CHAPTER 5. GENERAL CONCLUSIONS

The overall goal of this research was to collect information needed to improve the use of liquid swine manure as a source of P for crops and ultimately minimize the risk of P loss from fields as a consequence of excess or inadequate manure application. Two types of field experiments using different methodologies were conducted to achieve this general goal. The field and laboratory work as well as interpretation and summarization of results were developed to focus in three main areas of study. The objectives of one study were to evaluate liquid swine manure P effects on early plant growth, plant P uptake, grain yield, and P removal in corn-soybean rotations and at the same time evaluate crop response to P fertilization in addition to manure application. The objectives of a second study were to evaluate the impacts of liquid swine manure and fertilizer P application for corn-soybean rotations on soil P and to study how three routine soil P tests and two environmental soil P tests assess effects of manure or fertilizer P application on extractable soil P under crop production conditions. The objectives of the third study were to evaluate the effects of using variable-rate or fixed-rate methods of liquid swine manure application on the spatial variability of soil-test P and to adapt Markov random field models to examine the spatial dependence of STP after using these application methods.

Liquid swine manure and P fertilizer application increased early growth of corn and soybean, early plant P uptake, grain yield, and P removal in grain at few sites. This result was explained by soil-test P higher than needed to maximize growth and yield at many sites and because of very high initial soil-test P variability at some sites. Early plant growth and P uptake responses were not related to initial soil-test P, which is a result in agreement with previous research with P fertilization in Iowa. Study of plant responses with approximately similar rates of manure or fertilizer P indicated slightly higher and more frequent early plant growth increases for manured plots compared with fertilized plots, but the difference were small. Therefore, results of this study provided no evidence for a lower effectiveness of liquid swine manure P compared with P fertilizer for supplying P for early crop growth and, furthermore, some evidence for larger manure effect.

Grain yield response to manure application and to P fertilization were observed in soils testing optimum or less in soil test P according to current Iowa interpretations, with the only exception of one high-testing site where a response to manure was observed but not to P fertilizer. Large and highly probable response to P is expected in the low soil-test interpretation category and smaller and less frequent response to P is expected in the optimum category. Phosphorus fertilizer in addition to the high manure rates did not increase grain yield further at any site. The second-year crops after manure application seldom responded to residual manure P or to reapplied P treatments even though these treatments increased soil-test P significantly at most sites, which was a result we could not explain. The observed grain yield responses provided no evidence for lower availability of manure P compared with fertilizer P for grain yield. Also, an important result was that P fertilizer application in addition to manure rates that approximately supply N needs of corn did not increase grain yield further at any site.

Application of liquid swine manure or fertilizer P increased soil-test P measured after crop harvest in many sites. The Bray-1 and Mehlich-3 routine P tests tended to detect manure P effects on soil-test P more frequently than the Olsen routine test but the tests were similar at detecting soil-test P increases due to fertilizer P application. Results of regression analysis of soil-test P measured by each test after applying manure or fertilizer P at approximately similar rates showed no differences between manured and fertilized soils. Therefore this study provided no conclusive evidence for differences between tests at detecting soil-test P increases when manure of fertilizer P is applied to soils. Furthermore, these three routine tests and two environmental soil P tests assessed similarly extractable P from manured or fertilized soils, although the relative amounts of P extracted by the different tests were different. Correlations between soil P extracted by the tests were high and similar for unmanured, manured, or fertilized soils, and correlation coefficients were > 0.87 (correlations were lowest for Water extractable P).

The results of this study showed not conclusive evidence for differences between liquid swine manure or fertilizer as sources of P for corn soybean rotations as evaluated by early crop growth, grain yield, or P uptake by young plants or in grain. The results suggest that the availability of P in liquid swine manure is higher than the fraction proposed in many manure management guidelines.

The study that evaluated the effects of application methods of liquid swine manure on soil-test P showed that the variable-rate methods reduced soil-test P variability compared with the traditional fixed-rate method. The variable-rate method increased soil-test P more than the fixed-rate method in low-testing areas and usually did not affect soil-test P in high-testing areas. Therefore, this study demonstrated that variable-rate technology is a valuable tool to apply liquid swine manure because it allows for more efficient and environmentally sound P management. This study also demonstrated that conventional statistics as well as geostatistical and Markov random field models can be successfully used to study soil-test variability resulting from using different nutrient application methods.

Overall, this research successfully achieved its goals because results demonstrated that liquid swine manure is a valuable source of P for crops, that with careful management swine manure can be used instead of P fertilizer, and that it can be applied to fields with new application methods based on precision agriculture technologies and equipment that improve nutrient application.

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